

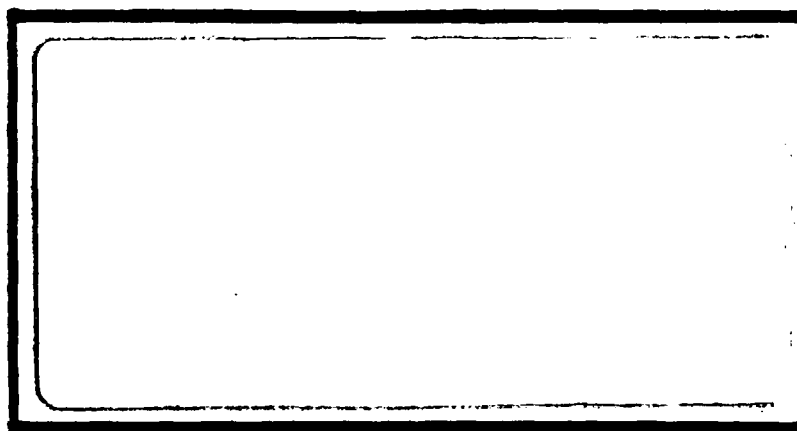
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A PARAMETRIC ANALYSIS OF A BALLOON DECOY AS A  
COUNTERMEASURE AGAINST AN INFRARED-GUIDED ANTI-  
SATELLITE WEAPON IN A GEOSYNCHRONOUS ORBIT

THESIS

David A. Agee  
Major, USAF

AFIT/GSO/PH/84D-1



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INFRARED-GUIDED ANTI-SATELLITE WEAPON IN GEOSYNCHRONOUS ORBIT

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Space Operations

David A. Agee, B.S.

Major, USAF

December 1984

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## Preface

The purpose of this thesis was to determine a balloon decoy criteria for an infrared-seeker-guided anti-satellite (ASAT) weapon attack against a target at geosynchronous altitude. The criteria was based on the balloon-to-source ratio, as seen at the output of the seeker detector.

I wish to thank my faculty advisor, Maj. James J. Lange, for his patience, advice and encouragement throughout the period of research. Also, my thanks to Mr. Kit Dustin for his help in preparing the final printed copy of this thesis.

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### Abstract

This thesis examined the correlation between selected parameters characteristic of an infrared-guided anti-satellite attack against a geosynchronous target. The countermeasure employed was a radiating balloon decoy. The criteria used to evaluate the parameters was the balloon-to-target ration, measured at the output of the seeker detector.

Coplanar orbits were assumed for the ASAT, target satellite and balloon decoy. The ASAT endgame was modeled and implemented on a digital computer.

Decoy parameters investigated were the weapon-target range when decoy was deployed, and the direction and magnitude of the decoy's velocity at ejection. The field of view of the seeker was also considered. Results provided a minimum balloon-to-target ratio needed to decoy the ASAT for variations in each parameter.

A PARAMETRIC ANALYSIS OF A BALLOON DECOY AS A COUNTERMEASURE AGAINST AN  
INFRARED-GUIDED ANTI-SATELLITE WEAPON IN GEOSYNCHRONOUS ORBIT

I. Introduction

Any object whose temperature is above absolute zero (-273 degrees celsius) radiates energy at all wavelengths of the electromagnetic spectrum. Most of this radiation is in the infrared portion of the spectrum, due to the temperature of the object and the resultant thermal action of its component particles.

Techniques which take advantage of the characteristic infrared radiation of objects have appealed to military planners since as early as World War I, since they offer opportunities for surveillance and tracking using portions of the electromagnetic spectrum not visible to the unaided human eye (26:464).

Infrared guidance systems take advantage of the ever-present, and constant, thermal signature of a target to provide tracking and guidance data to its host vehicle. An additional advantage of these systems is their ability to operate effectively over long ranges.

Sensors which are sensitive to long-wave infrared (LWIR) radiation, have been used to track orbiting spacecraft, to perform space-based surveillance and to guide "heat-seeking" aircraft attack missiles. Most recently, a homing guidance system which relies on an infrared sensor is being used on the U.S. miniature vehicle anti-

satellite weapon under development by the U.S. Air Force (57:25).

While current anti-satellite technology in use by the USSR is based on radar tracking of targets in low-earth orbits (LEOs), research continues in the USSR to develop infrared guidance systems for their anti-satellite weapons. Thus, there is evidence that U.S. space assets will realize an attack threat from an infrared-guided attack weapon sometime in the future (29:66-69).

With the emerging use of infrared guidance systems for attack missiles, methods have been developed to counteract the effectiveness of infrared sensors to track the thermal signatures of targets. One of these is the use of decoys which radiate energy equal to or greater than that of the primary target, creating false information about the location of the target (58:31).

Similarly, the use of decoys by space assets could provide an effective countermeasure to an infrared-guided attack weapon, by providing a thermal signature of equal or greater intensity than that of the primary target. A decoy, ejected away from the target with an initial positive velocity relative to the target would cause an infrared-guided weapon to track a point between the target and the decoy, just as a flare decoy would direct an infrared-guided missile away from its aircraft target.

The effectiveness of a decoy against an infrared-guided anti-satellite weapon is dependent on the intensity of the decoy, the range (weapon-target) at which the decoy is deployed, and the direction of deployment from the target.

## Background

The United States, particularly the military, has become dependent on space systems for much of its communication, intelligence and meteorological data. unprotected satellite resources, essential to sustained, successful military operations, are highly vulnerable to enemy attack (54:99).

Concern for the survivability and protection of U.S. satellites has held minor importance until the last decade. In the last ten years, the USSR has demonstrated a credible antisatellite (ASAT) attack capability against satellites in low-earth orbits (LEOs---less than 1000 nautical miles from earth) (16:44). Many of the U.S. satellites are in higher, geosynchronous orbits (GEOs), and are out of range of existing ASAT threats. However, the USSR is developing ASAT systems which can reach GEO satellites. Deployment of such a high-altitude ASAT will make virtually all U.S. satellites vulnerable to attack (29:69).

The potential to attack any U.S. satellite has prompted growing interest in improving satellite survivability. One method to improve a satellite's survivability is to develop specific passive or active countermeasures to an attack. Active countermeasures, such as attack of the ASAT before it "kills" a target, require much more sophisticated technology than passive measures, in which a "kill" is prevented by degrading or confusing the ASAT's guidance sensor (58). The technical simplicity of passive countermeasures over active ones makes them a logical first choice for consideration and analysis. Of the varieties of passive countermeasures proposed, one of the simplest examples is

that of a reflecting or radiating balloon which is deployed by a target satellite as the attacking satellite approaches it.

Existing USSR ASAT systems acquire and track satellite targets using reflected radar signals (29:66). Currently, however, the USSR is conducting research to develop an infrared sensor guidance system for which radiated infrared energy provides the data for acquisition and tracking (29:66-69). Thus, there is a credible potential for the USSR to develop and deploy an infrared-guided ASAT with the capability to attack satellite assets in geosynchronous orbits.

Past research about ASAT weapon countermeasures has fallen into three categories. The first is research which provides a broad summary of various conceptual systems which could negate an attack. Another category analyzes the infrared sensor characteristics needed to detect an ASAT weapon's presence and/or to direct a counterattack. The final category is research offering a cursory evaluation of performance during an "end-game" scenario---that portion of time just prior to the weapon's interception of its target.

"Broad summary" reports, while describing various countermeasures, including the use of decoys, have provided only general criteria and proposals for potential countermeasure systems (18; 21). "Sensor research" studies offer general conclusions about the suitability of decoys to counteract an anticipated ASAT threat (6; 42; 51). "End-game scenario" analyses model various potential ASAT countermeasures, and evaluate their effectiveness against an attack (22). While the performance characteristics of a balloon decoy have undergone cursory evaluation, conclusions have been based upon nominal parameter values,

and do not consider variations in those parameters, as does this research.

In addition, all countermeasure studies, whether or not addressing the use of decoys, have concentrated predominantly on ASAT encounters in low earth orbits, and not on encounters in the higher, geosynchronous orbits.

While the use of optical countermeasures against infrared-guided weapons in space has not been demonstrated with actual hardware applications, there has been substantial research on the use of such countermeasures to counteract an IR-guided missile attack on aircraft. Owing to the high radiative output of an aircraft engine exhaust, the chosen countermeasure has been to use a flare decoy.

One fundamental method used to evaluate the effectiveness of a decoy is to evaluate the ratio of decoy intensity to source (target) intensity which produce output at the seeker detector sufficient to decoy the seeker. This has been a primary means of evaluating flare effectiveness as a decoy (39:2-3).

The same balloon decoy-to-source signal ratio can be used similarly to evaluate the effectiveness of a decoy against a satellite weapon attacking an orbiting satellite. Its validity follows from consideration of the basic design of the ASAT weapon's infrared guidance system. Adjustment of its orientation, and changes in ASAT velocity during target tracking are initiated in response to signals received from the decoy and target, just as the missile guidance system acts in response to signals from the aircraft and flare.

## Objective

The objective of this thesis is to determine decoy criteria, based on the balloon decoy-to-target ratio as derived at the output of the seeker detector. An endgame engagement model will describe an encounter between a direct-ascent ASAT weapon and a target satellite in geosynchronous orbit. Critical parameters affecting the criteria will be identified, according to the ratio required to decoy the ASAT weapon. A computer program will be used to implement the endgame model.

## Assumptions

Fig. 1-1 illustrates the endgame encounter scenario. Key assumptions in the analysis are as follows:

- 1) Both the target and the weapon are coplanar---that is, orbits of both are in the same orbital plane.
- 2) The target vehicle is in a circular, geosynchronous orbit.  
(Earth center-to-target center distance is 42164 km.)
- 3) The apogee distance of the ASAT's orbit at the beginning of the endgame equals the altitude of the geosynchronous target vehicle.
- 4) Motions of ASAT weapon, target satellite and balloon decoy are described by the two-body central-force motion equations. Drag is negligible.
- 5) Velocity changes of the ASAT are instantaneous, in response to target and balloon position data from the seeker detector.
- 6) The criteria developed will be a balloon decoy-to-target (B/T) ratio at the output of the seeker which is needed to decoy the



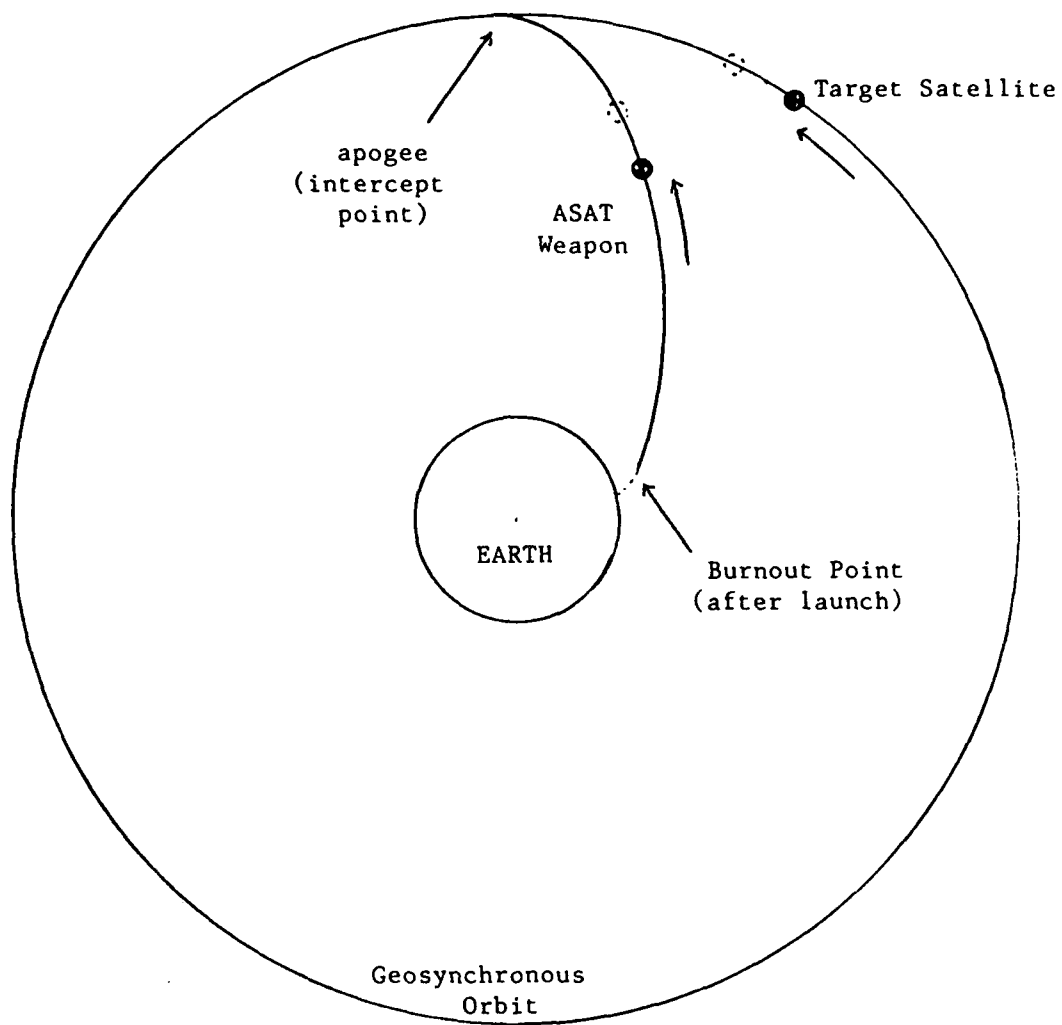


Figure 1-1. Apogee Intercept Endgame

seeker. Specific parameters of the detector will not be identified, but will be intrinsic in the B/T ratio.

- 7) The target satellite and balloon decoy are characterized as "greybody" radiators, with equal spectral intensities in the long-wave infrared region.

#### Procedure and Organization

Chapter Two describes the factors which enter into the calculation of the B/T ratio. Chapter Three develops balloon target and seeker models. A simplified sample endgame encounter is given in Chapter Four. Chapter Five presents a description of the computer program development. Results and Conclusions are presented in Chapters Six and Seven.

## 11. Determination of B/T Ratio

As this thesis uses the B/T ratio as seen at the output of the seeker detector, this chapter describes factors which affect the output, and a method to calculate the B/T ratio.

Radiation sources, such as the target satellite and the balloon decoy, emit radiation energy in all directions, travelling at the speed of light. The radiation energy passing through an area in a unit of time is called the radiation flux (through the area), and is denoted by  $\Phi$  [watts]. The radiant flux represents the power transmitted by the radiation. A radiation detector, if considered simply as an input-output unit, will produce an electric signal output ( $V_s$  in volts), which results from an input of radiant flux ( $\Phi_e$ ). In addition, a noise voltage,  $V_n$ , develops in a detector even when no radiant flux is incident on the detector. From these principles, the characteristics describing a particular radiation detector may be explained. These characteristics are the detector's responsivity ( $R$ ), noise equivalent power (NEP), detectivity ( $D$ ) and specific (or normalized) detectivity ( $D^*$ ) (56:110-111; 39:6-7).

The responsivity,  $R$ , of a detector is the ratio of output signal to the input incident radiant flux. Conditions which must be specified for a measured responsivity are the radiation source, its temperature, the modulation frequency of the radiant flux, and the operating temperature of the detector. In a similar manner, the spectral responsivity ( $R_\lambda$ ) is the detector responsivity corresponding to a

monochromatic radiation source of wavelength  $\lambda$  (56:110).

The noise equivalent power (NEP) indicates the minimum effective radiant flux incident on a detector which produces a signal equal to the noise voltage of the detector. This may also be described as the value of radiant flux needed so that  $V_s/V_n = 1$ . Conditions in effect at the time the NEP is measured are also specified, as in the case of a detector's responsivity.

Detectivity (D) is the ratio of the values of signal and of noise, when a radiant flux of 1 watt is incident on the detector. From the definition of NEP,

$$D = 1/\text{NEP} \quad [\text{watts}^{-1}] \quad (2.1)$$

For most detectors,  $\text{NEP} = (A\Delta f)^{1/2}$ , where A is the effective area of the surface of the detector, and  $\Delta f$  is the bandwidth of the electronic system.

The specific detectivity ( $D^*$ ) is defined as

$$D^* = (A\Delta f)^{1/2} / \text{NEP} = D (A\Delta f)^{1/2} \quad (2.2)$$

Specific detectivity is not dependent on the detector area or on the bandwidth of the electronic system. It represents a detectivity equivalent to the measured value, but it is normalized to correspond to a sensitive area of  $1 \text{ cm}^2$  and a 1 Hz bandwidth. Specific values of  $D^*$  for an incident radiation wavelength, source temperature and chopping frequency are readily available for typical detector materials. Figure 2-1 is a sample graph of  $D^*$ .

Given the detector material, area and bandwidth, D may be found

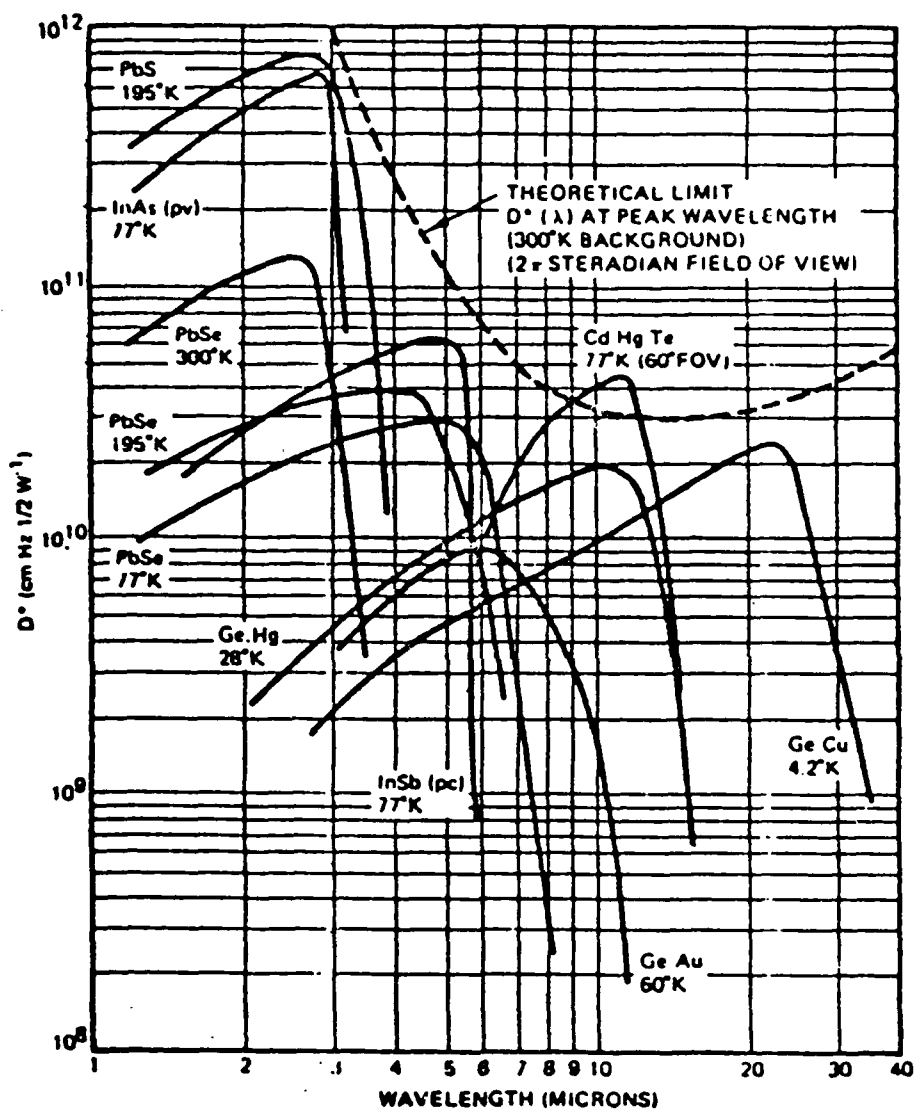


Figure 2-1 (Ref. 39). Spectral Detectivity of Infrared Quantum Detectors

using equation 2.2. Then, R is derived from

$$D = R/V_N \quad (2.3)$$

where  $V_N$  is the noise voltage (56:111).

An additional factor in determining the current at the detector output is the atmospheric transmittance of the radiation between the source and sensor detector. Given as a coefficient between 0 and 1, the transmittance represents the fraction of original transmitted radiation intensity which is incident on the sensor. Radiation transmittance decreases due to molecular absorption and scattering. Since molecular density decreases with altitude from the earth's surface, at the altitude of the endgame encounter (geosynchronous altitude), the molecular density is so low that the transmittance is very close to 1.

The two remaining factors are the spectral intensities of the target satellite and the balloon decoy. Both emit radiation due to their internal temperatures, which are affected by both the temperature of the space environment, and the heat created by any onboard energy sources and radiation incident upon it (such as solar). Although this study does not address the specific design characteristics of the balloon decoy, such as surface area, construction materials, or methods to maintain its temperature, the radiation characteristics of the balloon are assumed to be equivalent to that of the target satellite for the duration of the endgame. Both sources may be characterized as "greybodies" with a given emissivity. Additionally, they are modeled as point sources of radiation, owing to the target-sensor and

balloon-sensor ranges during the endgame. As point sources, the radiated power is inversely proportional to the square of the distance between the sensor and the source (target or balloon).

The actual signal levels at the output of the detector may be calculated, using the following expression (39:11-13):

$$i_s(t) = \int_{\lambda_1}^{\lambda_2} R(\lambda) T(\lambda) Q_s(t) I_s(\lambda, t) A \delta\lambda / r^2 \quad (2.4)$$

where  $i_s$  = signal voltage at output of detector due to a radiating source, s

$R$  = detector responsivity

$T$  = transmittance ( $\approx 1$ )

$Q_s$  = off-axis response of seeker

$A$  = projected area of detector

$I$  = intensity of source s

$r$  = detector-source distance

$\lambda_1, \lambda_2$  = wavelength bandpass of the sensor

This integral is calculated over the spectral bandpass of the sensor.

In general terms, as indicated by equation 2.4, the source intensity is a function of time. For the duration of the endgame encounter, the balloon and target intensities are assumed to have the same wavelength dependence over the selected spectral bandpass of the sensor.

Hence, if the B/T ratio is defined to be the ratio of balloon and target intensities, then

$$\frac{B}{T} = \frac{I_B}{I_T} \quad (2.5)$$

and

$$\frac{i_D(t)}{i_T(t)} = \frac{B}{T} \frac{Q(\beta(t))}{Q(\alpha(t))} \frac{r_T^2}{r_D^2} \quad (2.6)$$

where  $i_D$  = output signal due to decoy,

$i_T$  = output signal due to target,

$\alpha$  = angular displacement of the target satellite from the ASAT LOS,

$\beta$  = angular displacement of the balloon decoy from the ASAT LOS,  
and

$r_T, r_D$  = distance from ASAT weapon to target ( $r_T$ ) or balloon decoy ( $r_D$ ).

This study will investigate the balloon-to-target ratio as seen at the output of the detector. Implicit in this ratio are both transmittance and detector responsivity. Initially, at the time of balloon deployment, the B/T ratio will be 1, however, as the endgame progresses it will change. Changes in the B/T ratio will depend on the decoy ejection parameters employed---range at ejection and velocity (direction and magnitude) of the balloon at ejection time. This study will determine the parameters most sensitive to the B/T ratio, as well as the boundary values for B/T for which the weapon is effectively decoyed from hitting and destroying its target.



### III. Modeling of Seeker, Target and Decoy

The three vehicles in the ASAT endgame encounter---the ASAT seeker, target satellite and balloon decoy--- must be modeled to perform an analysis of the endgame.

#### Seeker

A characteristic LWIR seeker assembly (Figure 3-1) is composed of a germanium dome, rotating gyro-optics, head coils and a detector cooling system. Infrared radiation enters the seeker and reflects off the spinning primary and secondary mirrors onto a stationary reticle which modulates the energy. In providing modulation, the reticle (or "chopper", as it is also called) permits discrimination of the target angular and radial displacement relative to the seeker line of sight (LOS). The modulated radiation continues past the reticle onto a photoconductive detector composed of semiconductor material---HgCdTe, doped Ge or Si. The detector converts the incident energy into an electrical signal which is processed by the electronics of the seeker system. A slight tilt of the secondary mirror creates a conical scanning pattern of the image onto the stationary reticle, creating a nutation circle (Figure 3-2).

The signal processing amplifies, filters and demodulates the detector signal. If there is no pointing error, the target image travels around in a nutation circle which is concentric with the center of the reticle. The target image encounters the chopping segments at a

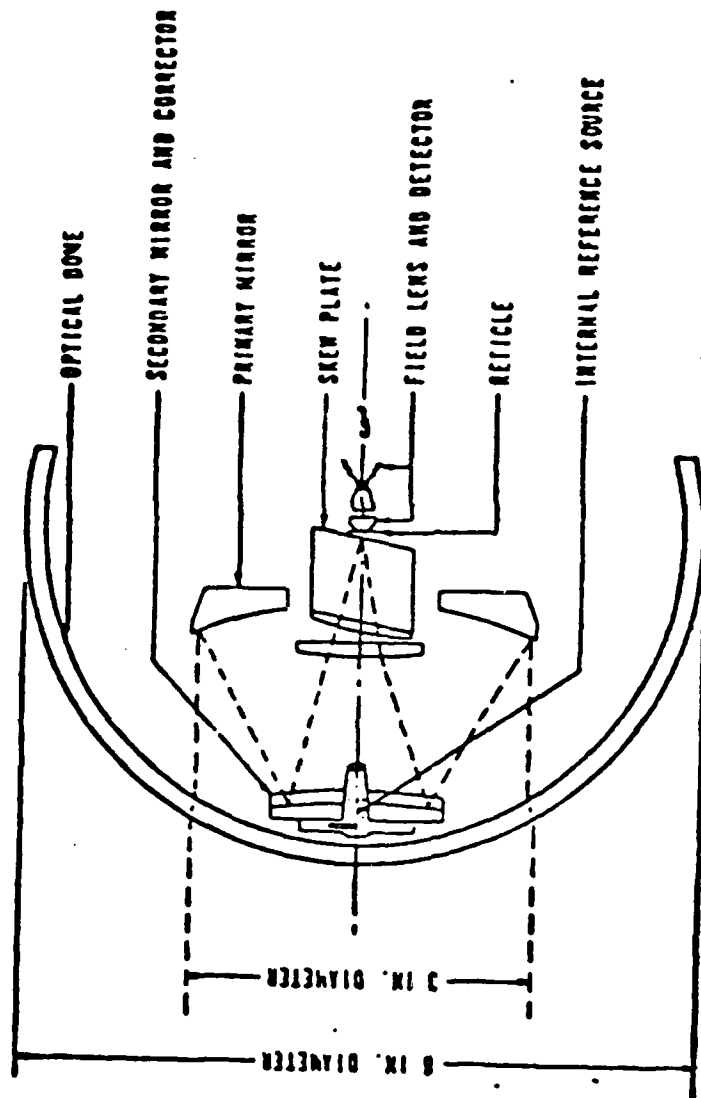


Figure 3-1 (Ref. 39:15) Seeker Optical System

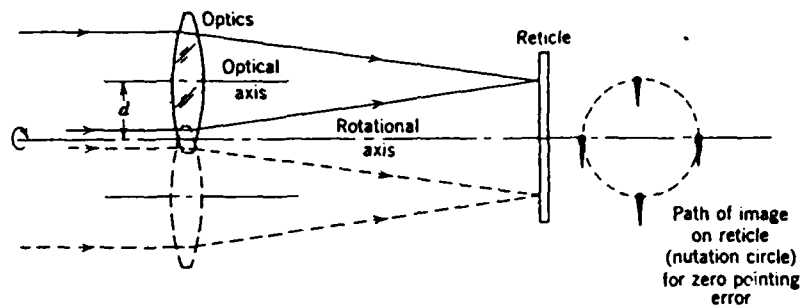


Figure 3-2 (Ref. 26:250) Rotation of Optics to Produce Nutation

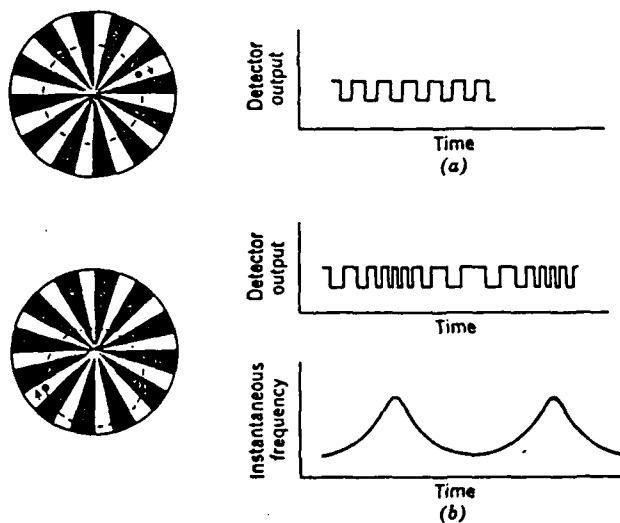


Figure 3-3 (Ref. 26:250). Frequency Modulation From Nutating System

constant rate and the detector output is a train of pulses of constant frequency (Figure 3-3a). If there is a pointing error, the nutation circle is no longer concentric with the reticle center. The smaller width of chopping segments near the center causes a detector output of varying frequency (Figure 3-3b). The phase of the frequency modulation is proportional to the angular location of the image, relative to the LOS. This becomes an error signal which is used to update the position of the seeker and guide it (and hence, the ASAT weapon) toward its target (39:14; 26:250-252).

Reticles may be designed to develop amplitude (AM) or frequency (FM) modulation, or a combination of both. AM reticle systems (Figure 3-4) track the centroid of multiple signals, but have better range capabilities. FM systems (Figure 3-3) usually have a higher signal-to-noise ratio than AM designs, but track the point of maximum intensity (39:16; 26:257). Depending on target and tracking system requirements, various reticle designs may be used effectively in the seeker assembly.

A seeker applicable for use on an ASAT weapon may be characterized by its velocity profile, off-axis response curve, tracking method (AM/FM) and frequency of seeker LOS update.

The velocity of the ASAT weapon/seeker is described by the orbital elements derived from the two-body equations of motion. A summary of astrodynamics principles used in the derivation of the computer model is presented in Appendix A.

The seeker off-axis response curve is a graphical representation of the seeker's response to incident energy as a function of the

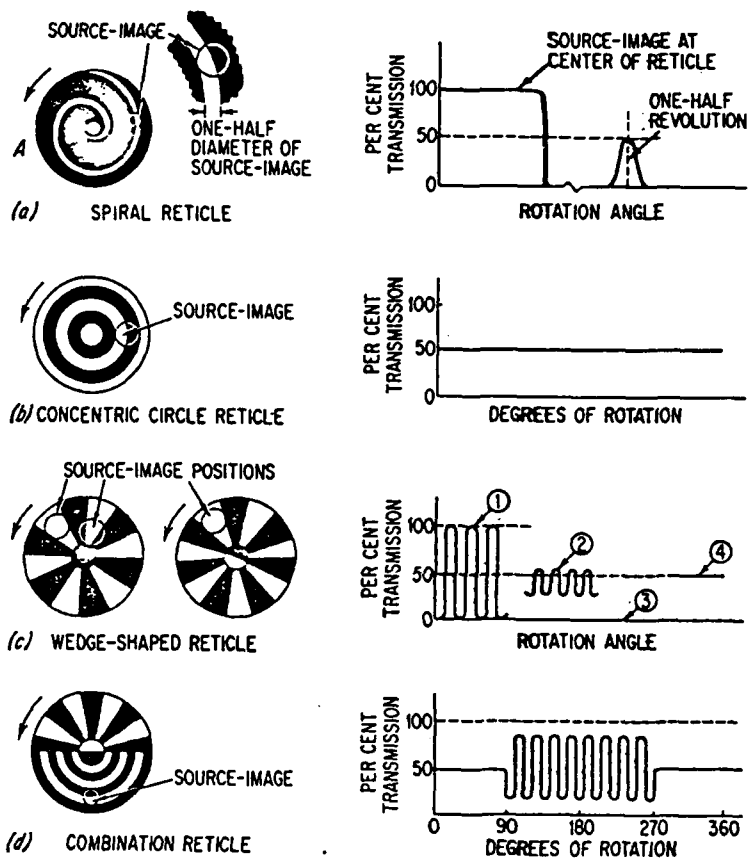


Figure 3-4 (Ref. 20:98). Reticles

target's angular displacement from the center of the seeker LOS. A representative seeker response curve and the corresponding model, as used in this analysis, is shown in Figure 3-5.

There are three distinct curve regions in the model used:

$$x = e^{-\theta/\theta_1}, \quad 0 \leq \theta \leq 20 \text{ milliradians} \quad (3.1)$$

$$x = \theta_2, \quad 20 \leq \theta \leq 40 \text{ milliradians} \quad (3.2)$$

$$x = \theta_2 - .015(\theta - 40) \quad 40 \leq \theta \leq 50 \text{ milliradians} \quad (3.3)$$

The model's input parameters are the angular displacement of the target from the seeker LOS ( $\theta$ ) and the seeker damping constant ( $\theta_1$ ). The damping constant describes the fall-off rate of the dying exponential portion of the model (Equation 3.1), and determines the value of  $\theta_2$  required for continuity. That is,  $x(\theta = 20 \text{ mrad}) = e^{-20/\theta_1} = \theta_2$ . A value of 10.5 mrad was selected to correspond to the model of the actual off-axis response curve, and hence,  $\theta_2 = 0.15$  (39:16-19).

Use of an AM reticle, permitting centroid tracking, is assumed for the seeker. The update cycle for the seeker is assumed every ten seconds after lock-on to the target satellite at 600 km range. The duration of the endgame from initial lock-on is approximately 4 minutes, during which the ASAT seeker LOS would be updated 24 times. While the program assumes instantaneous velocity changes, as needed to update the ASAT's position, a 10-second cycle further minimizes the effects of velocity changes which, in reality, would not be instantaneous.

The model further assumes that the ASAT has a capability to determine range to and velocity of the target, permitting determination of an off-axis distance and required velocity changes. This could be

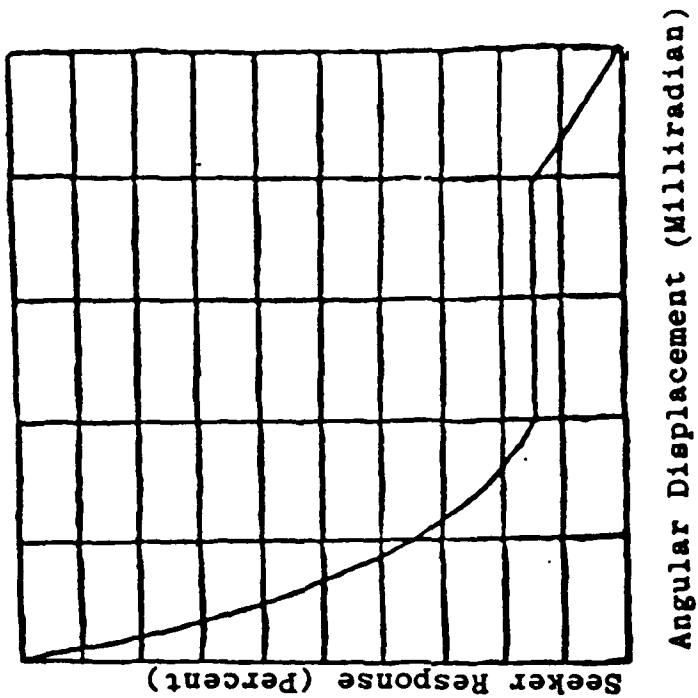
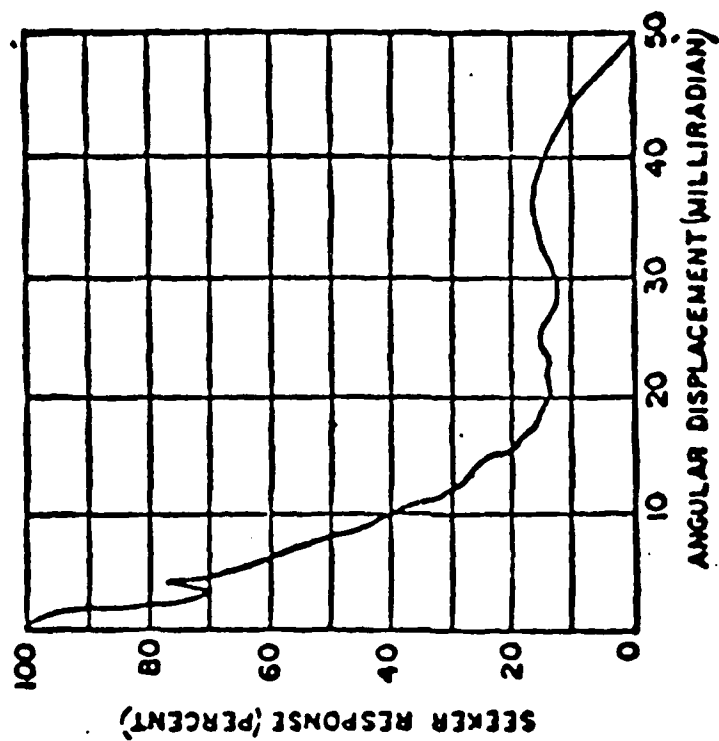


Figure 3-5 (Ref. 39:18). IR Seeker Off-Axis Response and Model

accomplished with a small radar.

Finally, one significant characteristic of the geosynchronous endgame requires additional explanation. The concepts used to develop guidance outputs for the ASAT are the same as those for the infrared-guided aircraft attack missile. For the aircraft-missile encounter, a higher missile velocity relative to the aircraft maintains a positive closing velocity, resulting in the missile over-taking its target. Guidance signals to the missile direct changes in its direction of forward motion. In an endgame between an ASAT weapon and a geosynchronous satellite target, the closing velocity ( $\approx 2$  km/sec) is maintained by a higher velocity of the target vehicle relative to the weapon. Guidance signals to the ASAT direct the weapon to position itself in the path of the approaching satellite target, causing a destructive collision between the two vehicles.

#### Target Satellite

The target satellite is characterized as a 5-meter-diameter sphere in a circular geosynchronous orbit. It performs no evasive maneuvers, and merely deploys the balloon decoy at a specified distance from the ASAT weapon. A ranging capability by the target satellite is assumed, permitting balloon decoy deployment at a particular range, but this study does not address the specific hardware requirements for this capability. The target's radiant intensity is assumed constant from initial lock-on to the completion of the endgame (i.e. the target is hit or weapon decoyed).



### Balloon Decoy

The balloon decoy is assumed to be ejected instantaneously from the target satellite upon reaching a specified range from the weapon. Acceleration time to achieve the ejection velocity (relative to the target weapon) is considered negligible. Once ejected, the balloon decoy continues in an orbit defined by its position and velocity at time of ejection.

The mechanics of ejection and the means to maintain the decoy's radiant intensity are not addressed in this study. The intensity of the balloon decoy is assumed constant from ejection time throughout the duration of the endgame.

#### IV. Sample Endgame Encounter

To illustrate the endgame geometry and the principles used in the computer program, a sample endgame encounter is described step-by-step. Characteristics of the ASAT weapon/seeker, balloon decoy and target vehicle are as follows:

**TARGET:**

Intensity = 1000 watts

**BALLOON:**

Intensity = 1000 watts

Ejection Range = 100 km

Ejection Velocity = 21 m/sec at 1.0 radians (from  
the direction of the target  
vehicle's velocity)

**ASAT SEEKER/WEAPON:**

Lock-On Distance = 600 km

Seeker Field of View = 2.5 degrees

Update cycle time = 10 sec

At initial lock-on, the seeker determines the off-axis angle of the target and calculates the velocity change required to center the seeker LOS on the target by the next LOS update cycle. The velocity change calculated and applied corrects the ASAT/seeker position so that its LOS would be centered on the target if the target were "fixed" in space. Since the target's position is continuously changing, according to its orbital motion, the changes in the ASAT/seeker velocity will not usually correct the LOS to be precisely centered on the target vehicle

by the next LOS update cycle.

This sample problem begins at the time of decoy ejection, at some interval after the seeker has locked onto the target. As described earlier, the LOS updates occur at 10-second intervals after initial target lock-on. For simplicity in describing the sample problem, it is also assumed that the balloon deployment occurs between LOS update cycles. Thus, at some time after balloon deployment (within 10 seconds), both the balloon and the target will be in the seeker field of view, and the LOS will be updated to the centroid of the intensities.

The relative positions of ASAT, target and balloon at the beginning of the endgame encounter are shown in Figure 4-1.

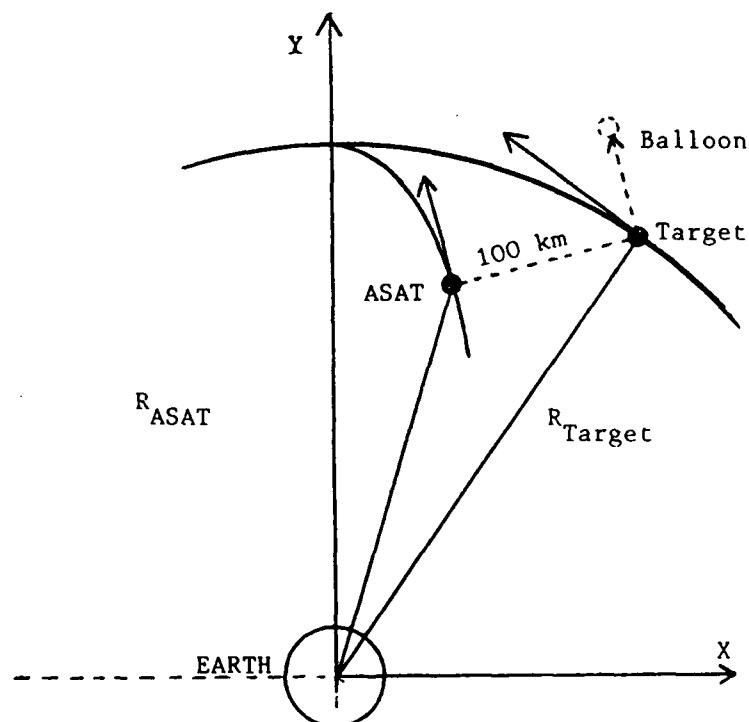


Figure 4-1. Endgame Positions

$t = 0$  sec (balloon decoy ejected)

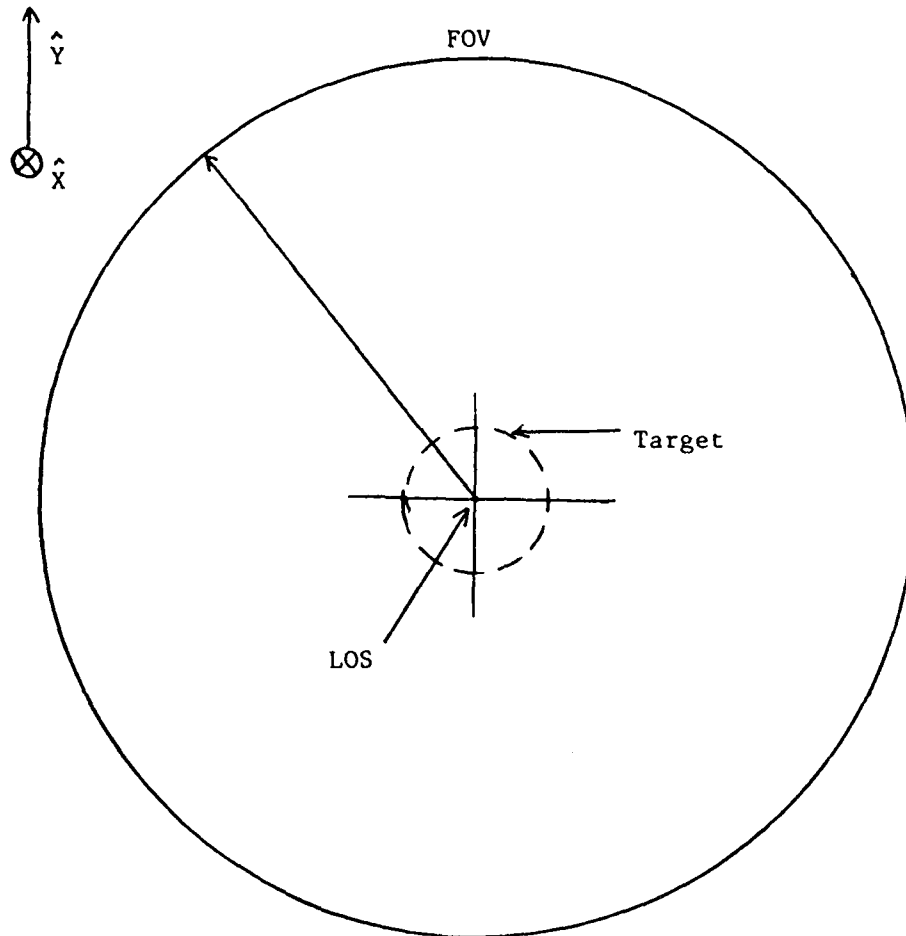


Figure 4-2. Seeker LOS ( $t = 0$  sec)

At  $t = 0$ , the balloon is ejected from the target satellite. Range to the ASAT weapon from the decoy and target is 100 km. The ASAT-target relative velocity is 2.149 km/sec.

$t = 6 \text{ sec}$

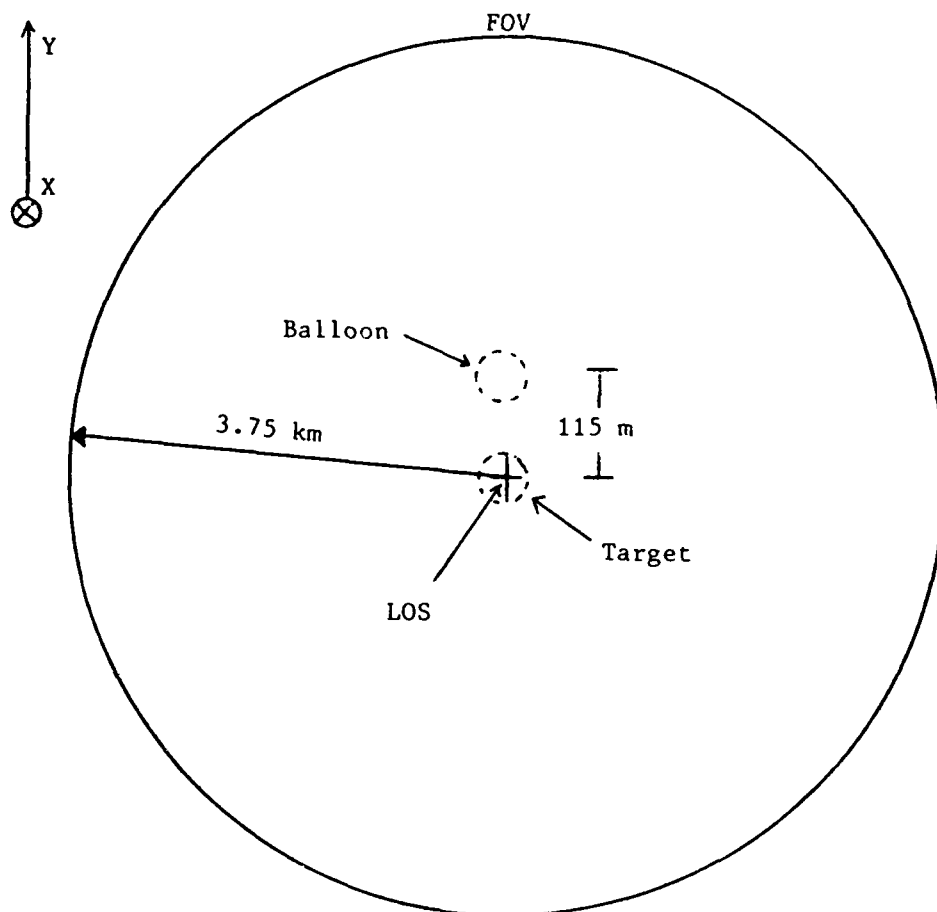


Figure 4-3. Seeker LOS ( $t = 6 \text{ sec}$ )

Six seconds after balloon deployment is the next LOS update cycle. At this time, the range is 86 km. The seeker LOS, which remains pointed in the direction of the x-axis, is centered on the target satellite. However, the balloon, due to the y-component of its ejection velocity is separated from the target, and is 1.34 millirads offset from the seeker LOS. At 86 km, this corresponds to a 115 m

lateral displacement from the target in the y-direction. The seeker provides guidance information based on the calculated centroid of the balloon and target. The seeker response for the target is 100%, since the LOS is still centered on the target. The seeker response for the balloon decoy, offset 1.34 mrad, is 88%. The centroid is

$$\frac{(.88)(1000)}{(.88)(1000) + (1.0)(1000)} \times (115\text{m}) = 54 \text{ meters}$$

above the seeker LOS. To move 54 m by the next update cycle (10 sec later), the velocity change required is 5.4 m/s in the +y direction.

$t = 16 \text{ sec}$

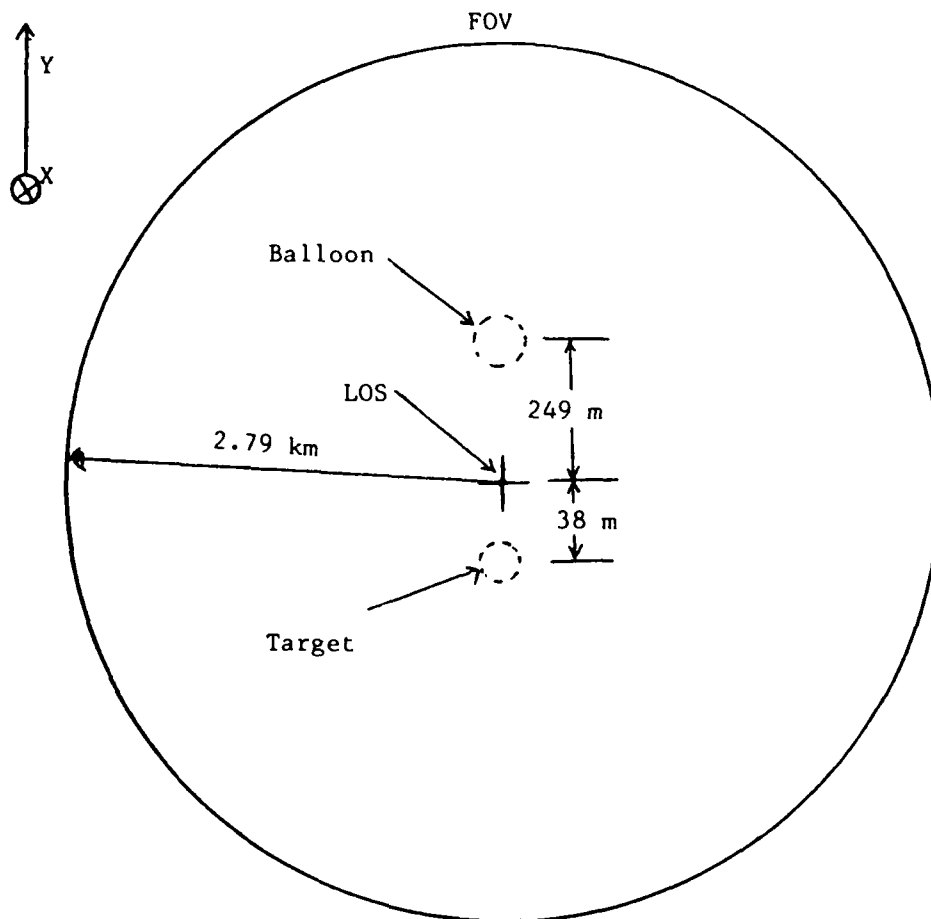


Figure 4-4. Seeker LOS ( $t = 16 \text{ sec}$ )

At the next LOS update time, the range is 64 km. The position of the target satellite is .6 mrad "below" (in the -y direction) the center of the seeker LOS. This corresponds to a 38 m lateral displacement at 64 km. The balloon decoy is 3.9 mrad "above" the center of the seeker LOS, thus displaced 249 m in the +y direction. For the target, the seeker response is 94%. The seeker response for the

balloon is 69%. The new centroid is

$$\frac{(.69)(1000)(249) - (.94)(1000)(38)}{(.69)(1000) + (.94)(1000)} = 83 \text{ meters}$$

above the LOS. The velocity change required is 8.3 m/sec in the +y direction.



$t = 26 \text{ sec}$

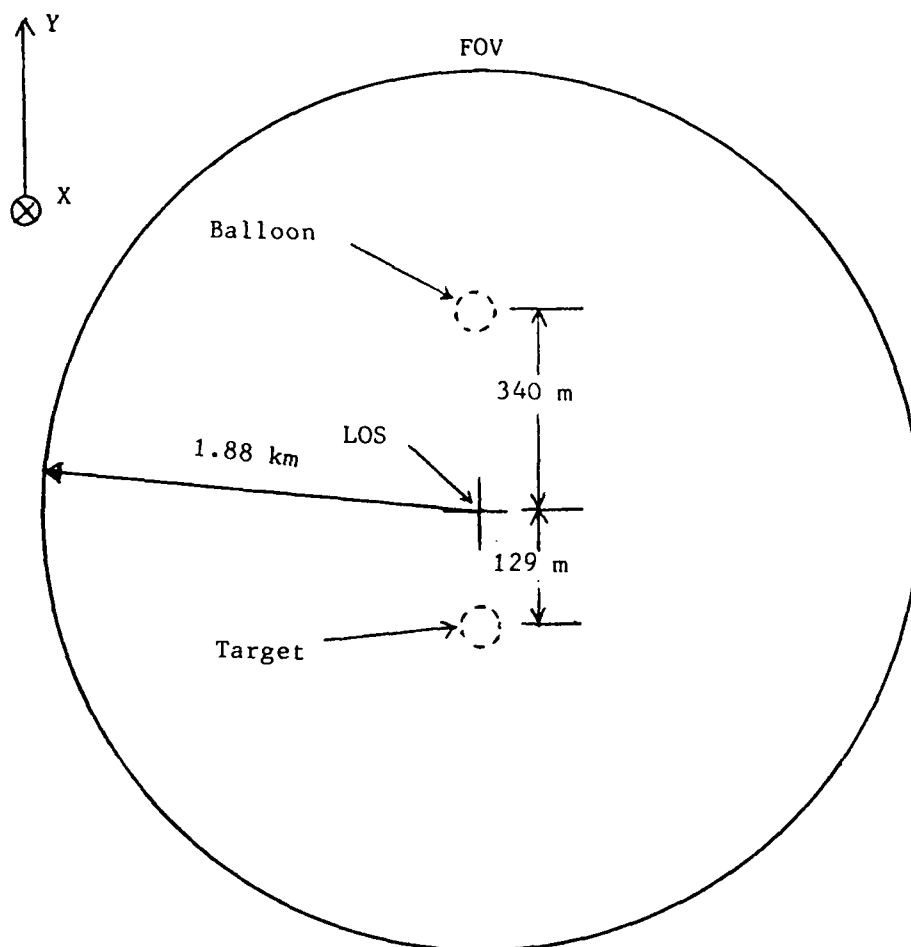


Figure 4-5. Seeker LOS ( $t = 26 \text{ sec}$ )

At the next LOS update, the range is 43 km. The target is 3 mrad below the seeker LOS, corresponding to a 129 m displacement in the  $-y$  direction. The balloon decoy is 7.9 mrad above the seeker LOS, and is displaced 340 m in the  $+y$  direction. The seeker response is 75% for the target and 47% for the balloon. Thus the new centroid is

$$\frac{(.47)(1000)(340) + (.75)(1000)(129)}{(.75)(1000) + (.47)(1000)} = 52 \text{ meters}$$

above the LOS. The required velocity change is 5.2 m/sec in the +y direction.

$t = 36 \text{ sec}$

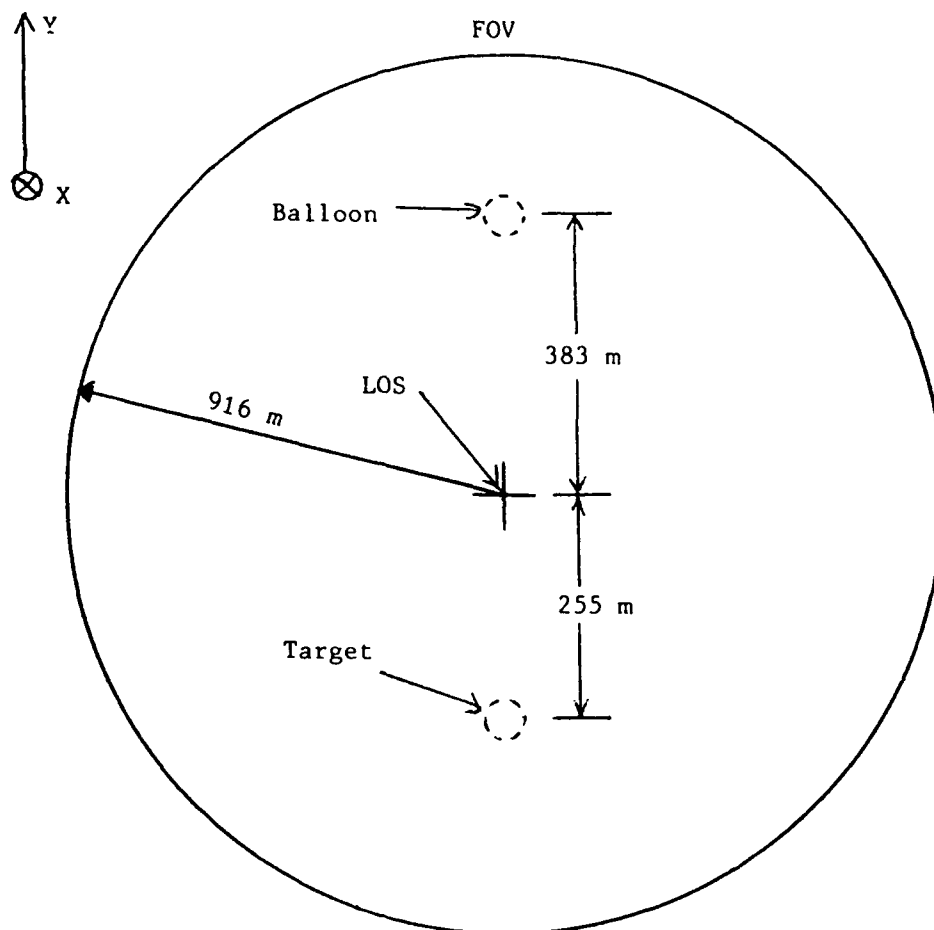


Figure 4-6. Seeker LOS ( $t = 36 \text{ sec}$ )

At the next LOS update cycle, the range is 21 km. The target is 12.1 mrad below the seeker LOS, displaced 255 m. The balloon is 18.3 mrad above the seeker LOS, and is displaced 383 m. Seeker response is 31% for the target and 18% for the balloon. The new centroid is

$$\frac{(.18)(1000)(383) + (.31)(1000)(255)}{(.31)(1000) + (.18)(1000)} = -21 \text{ meters}$$

or 21 meters below the seeker LOS. The velocity change required is 2.1 m/sec in the -y direction.

$t = 46 \text{ sec}$

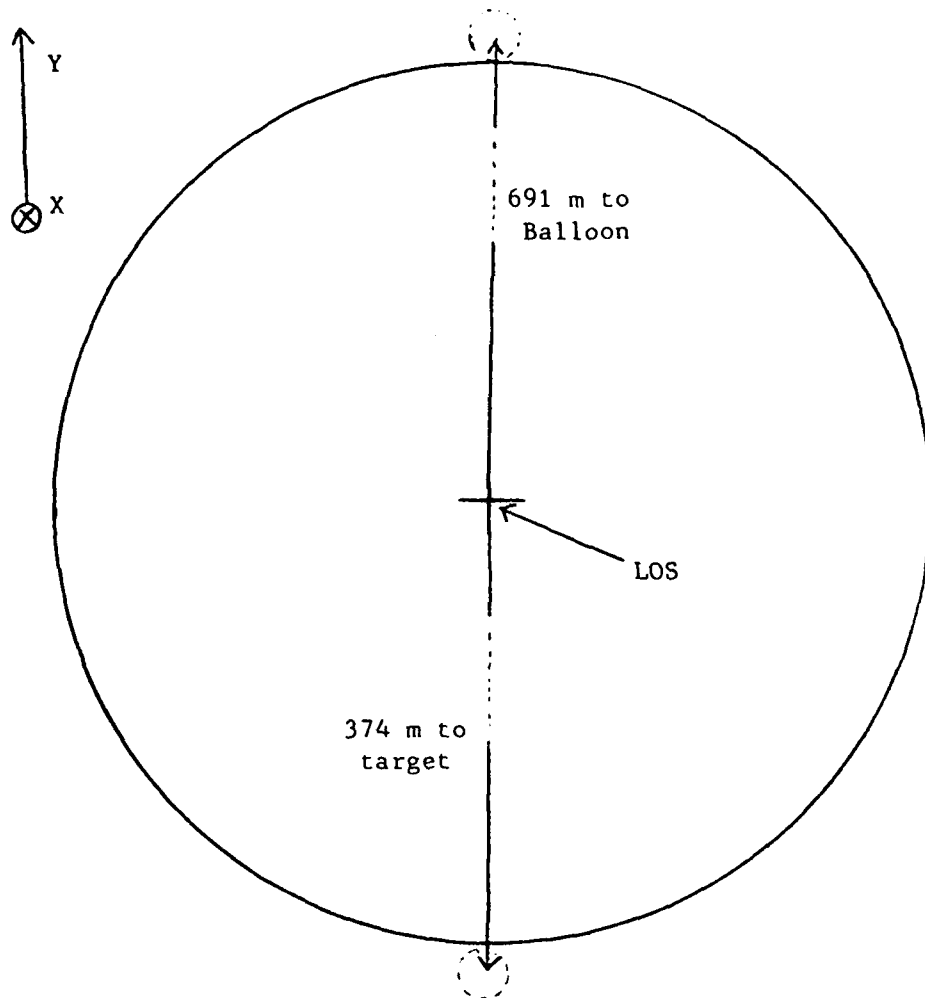


Figure 4-7. Seeker LOS ( $t = 46 \text{ sec}$ )

The range now is 0 km. At this time, the balloon is 691 m and the target is 374 m from the ASAT weapon. Thus, the target does not strike the weapon, and the ASAT is decoyed from hitting the target satellite.

## V. Development of Computer Program

### Intercept Geometry

The geometry of the ASAT weapon endgame problem is shown in Figure 5-1. From the time of initial target lockon, the seeker provides guidance inputs to maintain the center of the LOS on the target. After balloon deployment, the seeker tracks the centroid of the balloon and target. The guidance information provided directs velocity changes to the ASAT weapon to align the center of the LOS on the centroid of the two radiation sources.

To simplify the geometry, the following assumptions were made:

- 1) Motions of the target satellite, the balloon decoy and the ASAT weapon are described by the two-body central force equations. Gravitational interaction between satellite and balloon is negligible.
- 2) At the onset of the endgame, the orbits of the ASAT weapon and the target satellite are coplanar.
- 3) Velocity changes imparted to the balloon (at initial ejection) and to the ASAT weapon (when the LOS is updated) are made within the plane of the orbits. Thus, all three vehicles travel in coplanar orbits throughout the endgame.
- 4) The apogee of the ASAT weapon's orbit prior to target lockon equals the distance of the target satellite's circular geosynchronous orbit from the earth.
- 5) The coordinate system used for the endgame analysis is earth-

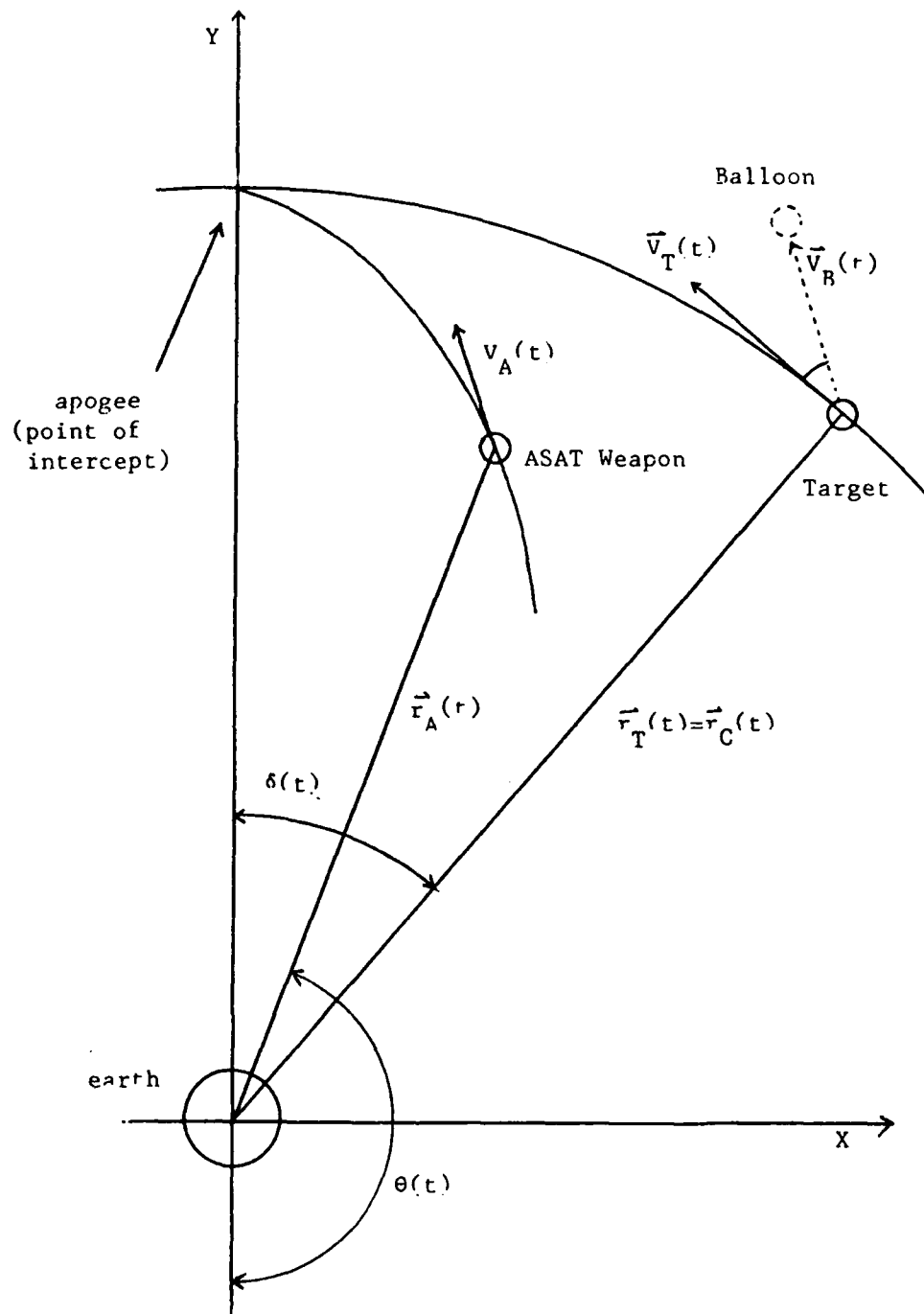


Figure 5-1. Endgame Geometry

centered, with one axis passing through the apogee of the ASAT weapon orbit.

- 6) The direction of the LOS of the ASAT seeker remains fixed in the coordinate system (i.e. the ASAT is stabilized and velocity changes are made in a direction perpendicular to the fixed LOS direction).

These assumptions make the problem a two-dimensional intercept problem. Position and velocity values for all three vehicles may be calculated for any time during the endgame.

To effect an intercept at the ASAT orbit's apogee, the ASAT weapon must be launched so that when it reaches the apogee of its original (unperturbed) orbit, the target satellite and the ASAT weapon are at the same point. This point corresponds to the intersection of the y-axis and the target satellite's orbit (See Figure 5-1.).

#### Target Satellite Geometry

Since the target satellite travels in a circular orbit, its angular velocity is  $2\pi/T$  [rads/sec], where  $T$  is the period of a geosynchronous orbit. Then,  $t$  seconds prior to apogee time, the target will be  $\delta$  radians displaced from the y-axis, where  $\delta$  is  $2\pi t/T$ . The magnitudes of the target's velocity and distance from earth remain constant (since it is geosynchronous). At any time  $t$  from intercept, there will be a corresponding  $\delta(t)$ , and the components of the target's position and velocity will be

$$r_x(t) = r_c \sin \delta(t) \quad (5.1)$$



$$r_y(t) = r_c \cos \delta(t) \quad (5.2)$$

$$v_x(t) = -v_c \cos \delta(t) \quad (5.3)$$

$$v_y(t) = v_c \sin \delta(t) \quad (5.4)$$

where  $r_c$  is the target-earth distance and  $v_c$  is the circular velocity (See Figure 5-2).

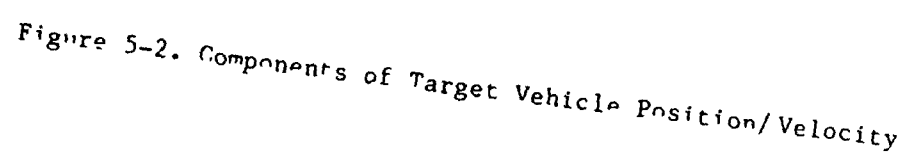
### Balloon Decoy Geometry

The balloon decoy, prior to its ejection, has the same velocity and position vectors as the target vehicle, traveling in its circular orbit. The velocity applied to the balloon decoy to eject it from the target causes the decoy's trajectory to change from a geosynchronous, circular orbit to another, slightly eccentric orbit (i.e. almost circular). The direction of the ejection velocity is given by an angle ( $\lambda$ ), outward from the target's velocity direction as the time of ejection (See Figure 5-3.). The decoy ejection velocity relative to the target satellite ( $\vec{V}_E$ ), and the decoy's initial velocity (i.e. target vehicle velocity) at the time of ejection, together define a new orbital trajectory for the decoy. This resultant vector sum ( $\vec{V}_B$ ), and the position vector at that time ( $\vec{R}_B$ ), correspond to 'initial conditions' for the orbit which the decoy will follow for the remainder of the endgame. The velocity components of  $\vec{V}_B$  will be

$$(V_B)_x = -V_c \cos \delta_0 - V_E \cos (\delta_0 + \lambda) \quad (5.5)$$

$$(V_B)_y = V_c \sin \delta_0 + V_E \sin (\delta_0 + \lambda) \quad (5.6)$$

where  $V_c$  is the circular velocity of the target satellite,



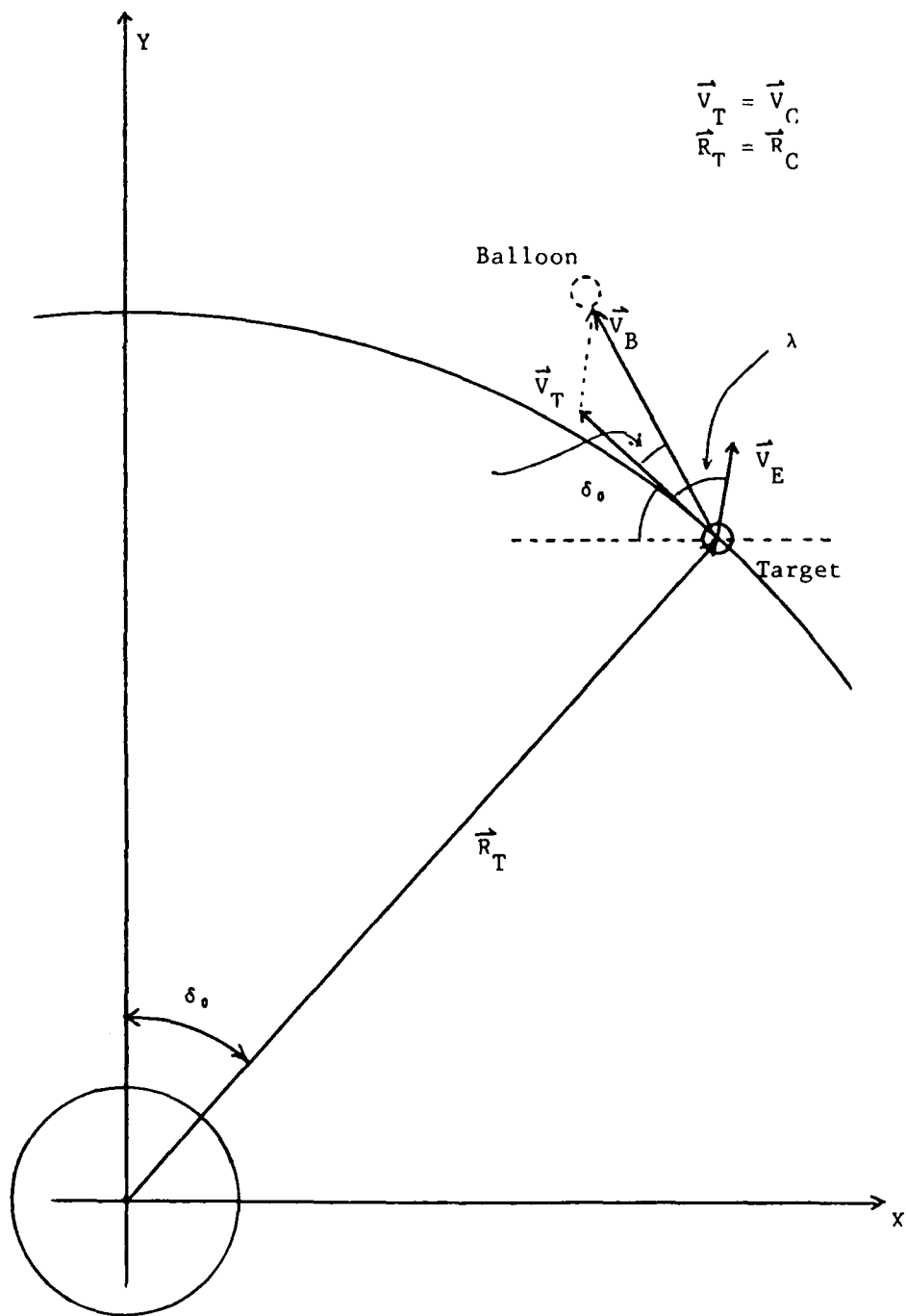


Figure 5-3. Velocity Componenters of Balloon Decoy at Ejection

$V_e$  is the ejection velocity of the balloon decoy,  
 $\delta_0$  is the angular displacement of the target at ejection time,  
 $\lambda$  is the decoy ejection angle (relative to target velocity direction).

Since the ejection velocity is applied instantaneously (by assumption), the position vector components of the decoy will be the same as those of the target at ejection time.

One additional parameter needed to calculate the elements of the decoy's orbit is the flight path angle,  $\beta$  (See Appendix A.). This may be determined using the relation

$$\beta = \arctan [ |(V_e)_y| / |(V_e)_x| ] - \delta_0 \quad (5.7)$$

As described in Appendix A, once the eccentricity and semimajor axis of the decoy's orbit are calculated, position and velocity may be determined for any subsequent time.

One complication which may result, however, is that the semimajor axis of the decoy's orbit may not coincide with that of the ASAT's orbit, on which the coordinate system is based. An example of a decoy orbit which illustrates this is shown in Figure 5-4. At ejection time, the decoy's position and velocity components may be expressed as a function of  $\delta_0$ , the target's angular displacement from the y-axis (i.e. the ASAT orbit's major axis). For any time after ejection, since the major axis of the decoy's new orbit may not coincide with an axis of the coordinate system, the components at that time must be defined as functions of additional parameters.

If  $t_e$  is the ejection time,  $\delta_0$  is the displacement angle at

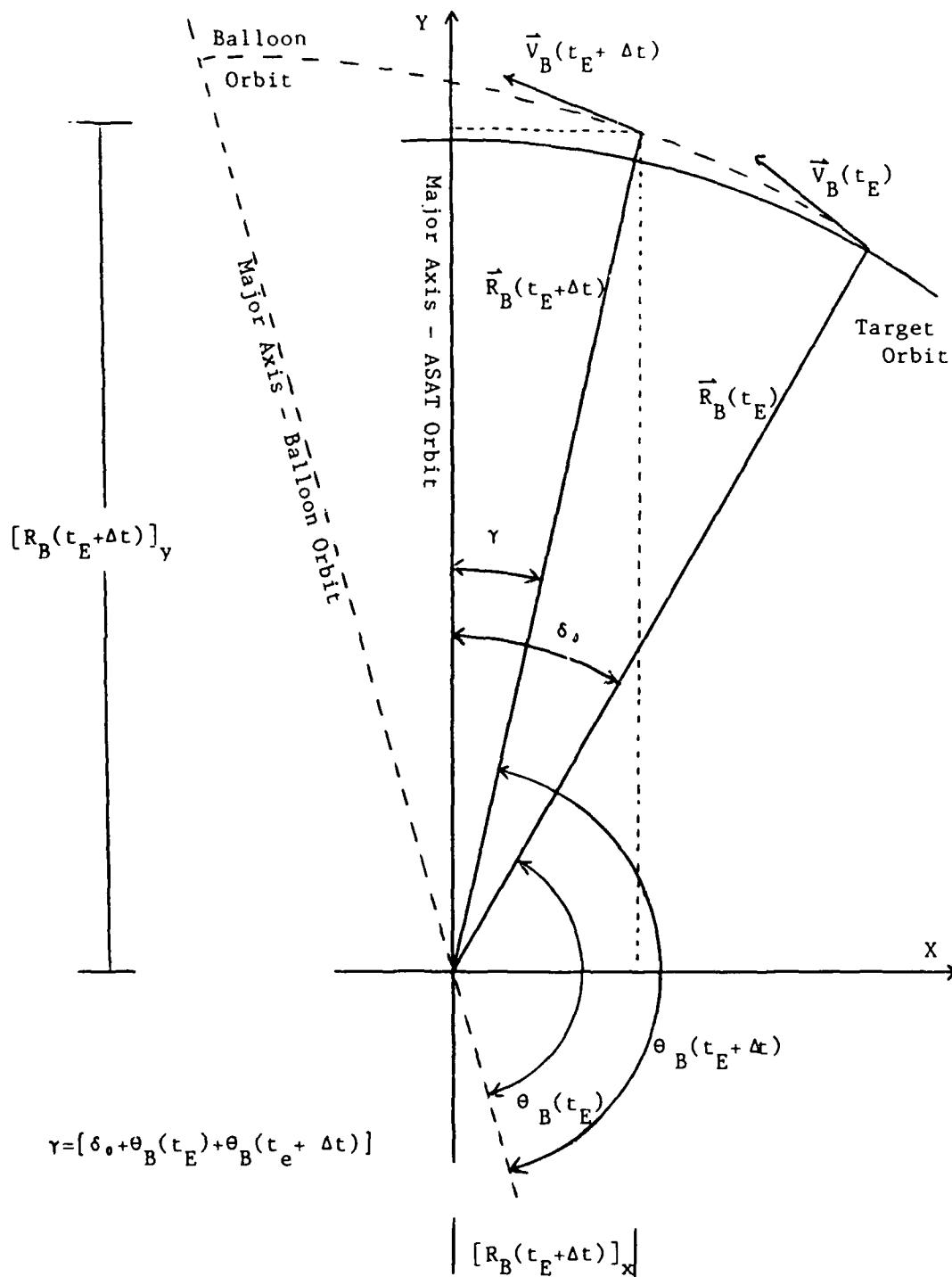


Figure 5-4. Balloon Decoy Position Components after Ejection

ejection (as described earlier), then, at time  $t_E + t$ , the decoy's position components are given by

$$[R_\beta(t_E + \Delta t)]_x = [R_\beta(t + \Delta t)] \sin [\delta_0 + \theta_\beta(t_E) - \theta_\beta(t_E + \Delta t)] \quad (5.8)$$

$$[R_\beta(t_E + \Delta t)]_y = [R_\beta(t + \Delta t)] \cos [\delta_0 + \theta_\beta(t_E) - \theta_\beta(t_E + \Delta t)] \quad (5.9)$$

where  $R_\beta(t_E + t)$  is the decoy-earth distance at time  $(t_E + \Delta t)$ ,

$\delta_0$  is the angular displacement of target (and decoy) at ejection time,  $t_E$ ,

$\theta_\beta(t_E)$  is the true anomaly of the balloon decoy orbit at time  $t_E$ , and

$\theta_\beta(t_E + t)$  is the true anomaly at time  $(t_E + t)$ .

Similarly, the velocity components for time  $(t_E + t)$  are given by

(See Figure 5-5):

$$[V_\beta(t_E + \Delta t)] = [V_\beta(t_E + \Delta t)] \cos [\pi - \delta_0 - \theta_\beta(t_E) + \theta_\beta(t_E + \Delta t) - \beta(t_E + \Delta t)] \quad (5.10)$$

$$[V_\beta(t_E + \Delta t)] = [V_\beta(t_E + \Delta t)] \sin [\pi - \delta_0 - \theta_\beta(t_E) + \theta_\beta(t_E + \Delta t) - \beta(t_E + \Delta t)] \quad (5.11)$$

where  $V_\beta(t_E + \Delta t)$  is the velocity at time  $(t_E + \Delta t)$ , and

$\beta(t_E + \Delta t)$  is the decoy's flight path angle at time  $(t_E + \Delta t)$ .

The values of  $V_\beta$ ,  $R_\beta$ ,  $\theta$  and  $\beta$  are determined from the time  $(t_E + \Delta t)$  and elements of the decoy orbit, as described in Appendix A.

#### ASAT Weapon Geometry

The technique used to compute the position and velocity components of the ASAT weapon are quite similar to that described for use with the

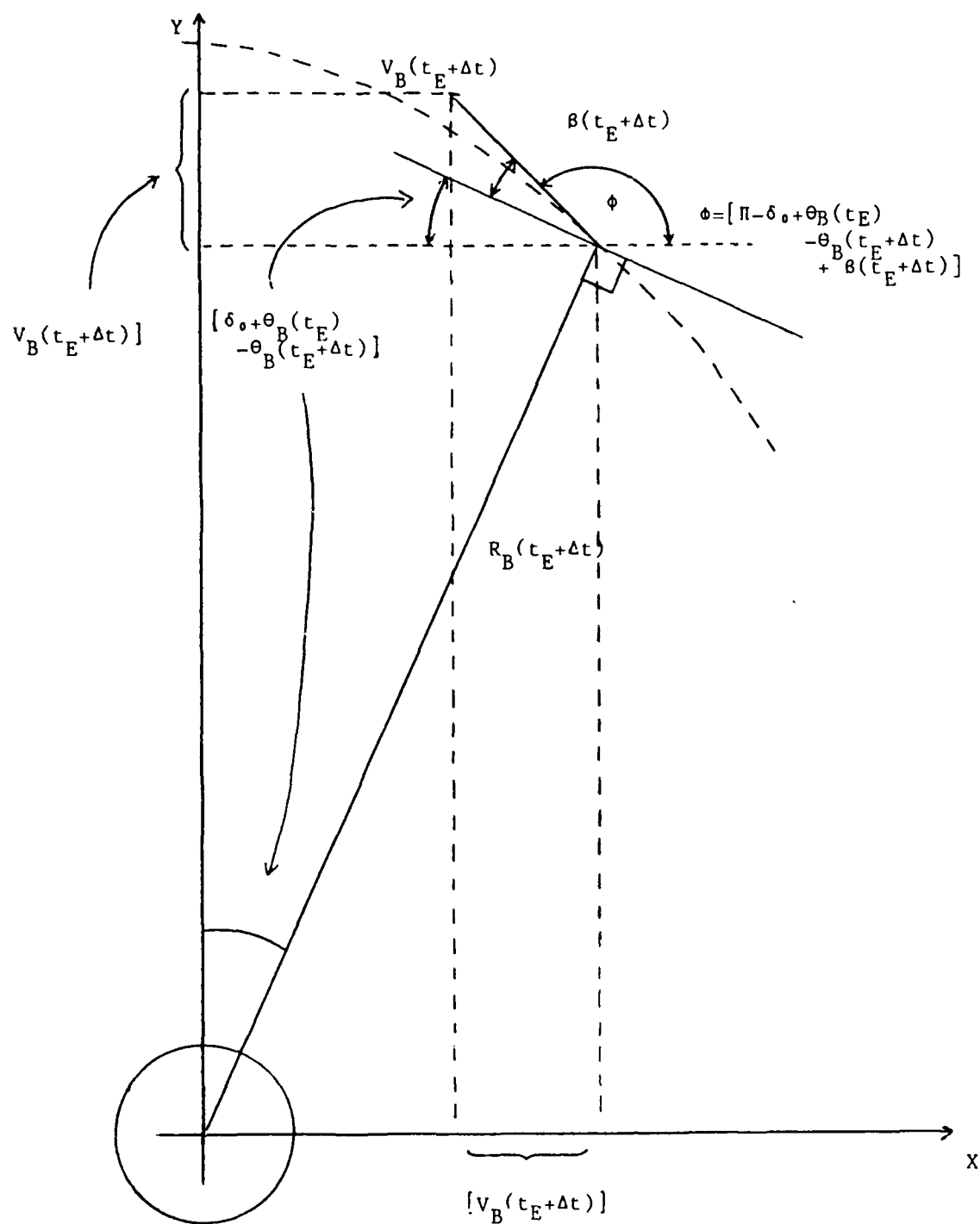


Figure 5-5. Balloon Decoy Velocity Components after Ejection

balloon decoy calculations. During freeflight (i.e. prior to any velocity changes), the major axis coincides with the y-axis, and the components are determined using calculated values for various orbit parameters (F, E, V, R) for the desired time.

When an impulse is applied to the ASAT weapon, per guidance information from the seeker system, the orbit resulting from the velocity change is described by new orbital elements  $a$  and  $e$ , as computed using equations A.7 and A.8 in Appendix A. The ASAT's position and velocity at the time of velocity change, together with the new values for  $a$  and  $e$ , become "initial conditions" which describe the new orbit.

As was the case for the balloon decoy orbit, the velocity change to the ASAT vehicle may describe a new orbit whose major axis is not aligned with an existing coordinate axis. Values of the true anomalies for the time and orbit when the velocity is applied and also for the time at which position/velocity information is desired define a "correction factor" which is used to calculate the component values. Since multiple, successive velocity changes are applied to the ASAT weapon, the effects of the correction factors are cumulative--- at any specified time, the calculation of position and velocity components will include correction factors for all preceeding velocity changes.

A simple two-velocity-change example, illustrated in Figure 5-6, demonstrates the process used to calculate ASAT position components. At a time  $t_1$ , the ASAT is in its original orbit (A), at position  $\vec{R}_1$ , when a velocity change  $\Delta v_1$  is applied. The known orbital elements of orbit A permit direct calculation of  $\theta_1(t_1)$ , and  $R_1(t_1)$ . The applied velocity changes the ASAT's trajectory to orbit B, whose major (and



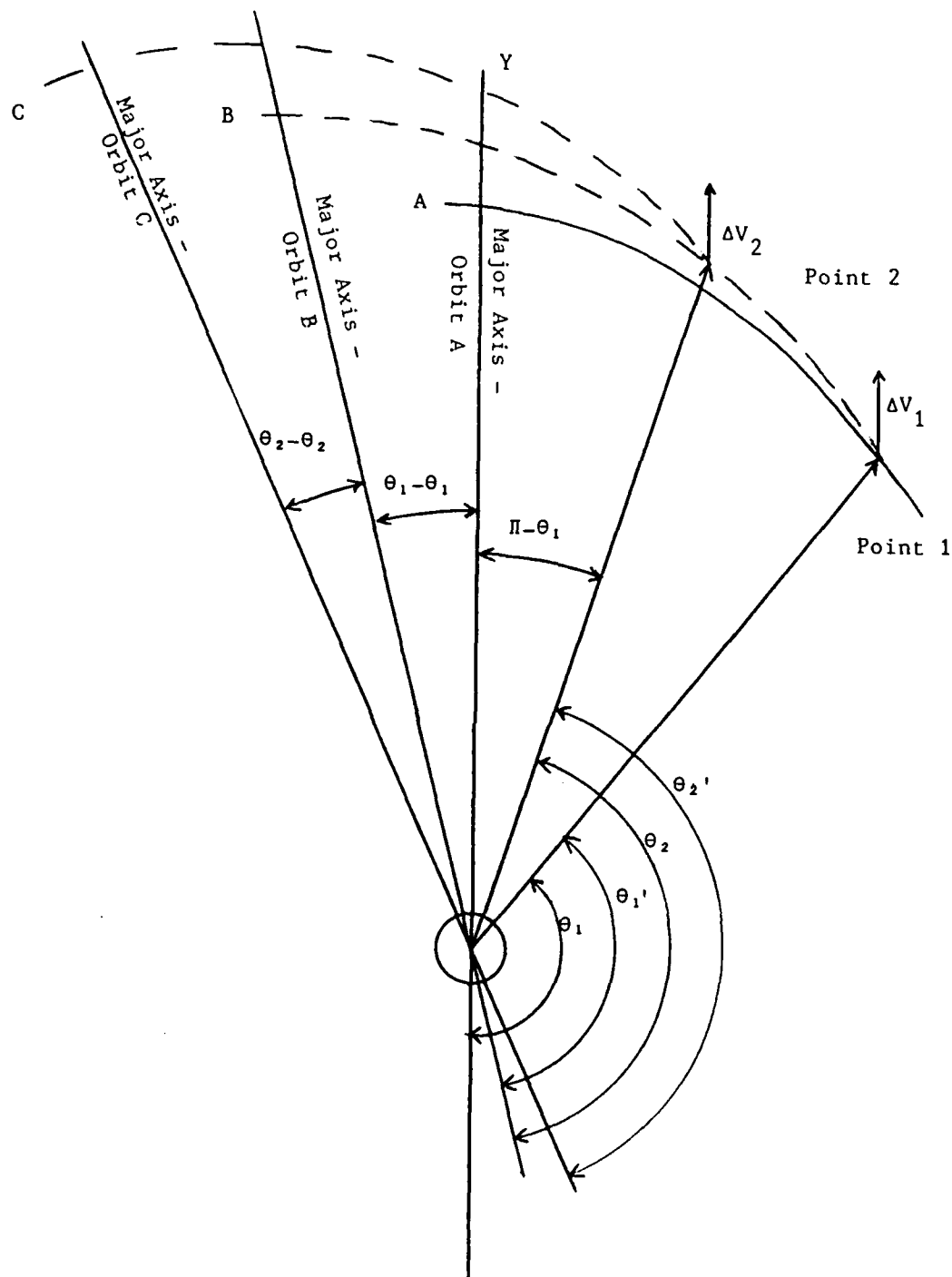


Figure 5-6. ASAT Weapon Position Components

semimajor) axis no longer coincides with the y-axis. The new ASAT velocity and the existing position of the ASAT, recalling that changes are instantaneous, determine the orbital elements for orbit B. At time  $t_1$ , the true anomaly with respect to orbit B is  $\theta_1'$ , and the major axis of orbit B is offset from the y-axis by a value  $(\theta_1 - \theta_1')$ .

At time  $t_2$ , the ASAT receives a velocity change  $\Delta v_2$ , which changes the ASAT's trajectory from orbit B to orbit C. At this time, if  $\theta_2$  is the true anomaly of the ASAT's position relative to orbit B, and  $\theta_2'$  is the true anomaly relative to orbit C (the new trajectory), then the major axis of C is offset  $(\theta_2 - \theta_2')$  from the major axis of B. Thus, C's major axis is offset  $(\theta_1 - \theta_1') + (\theta_2 - \theta_2')$ , indicating the 'additivity' of the correction factor. For time  $t_2$ , the position components will then be

$$(R_2) = R_2 \sin [\theta_2' + (\theta_1 - \theta_1') + (\theta_2 - \theta_2')] \quad (5.12)$$

$$(R_2) = R_2 \cos [\theta_2' + (\theta_1 - \theta_1') + (\theta_2 - \theta_2')] \quad (5.13)$$

As before,  $R_2$  is the ASAT-earth distance, as calculated from the elements of orbit B. Ensuing velocity changes will each produce an additional correction to be applied in calculation of the position components.

The equations used to calculate the velocity components require similarly derived correction factors, but include an additional term. Because the direction of the ASAT's velocity at any time is determined by the flight path angle ( $\beta$ ), its value, as calculated from the orbital elements in effect prior to the velocity change, will be included in the expressions for the velocity components. (The procedure is

analogous to the one used to derive the balloon's velocity components.)

While this example addresses one particular set of cases (velocities successively applied in the +y-axis direction), other cases arise, dependent on the  $v$  applied, in which the major axes of the "new" orbits will change back and forth about the y-axis. However, the use of a cumulative correction factor still applies in computing the velocity components.

Finally, although the description of time given at the beginning of this chapter was "time to intercept", the epoch chosen as the "starting time" is the time of perigee passage for the ASAT, in line with standard astrodynamics principles. All remaining times (e.g. burnout, intercept time, elapsed times) may be mathematically derived from the orbital parameters and the time of perigee passage. A sample program output (Appendix C) indicates time in terms of both burnout time and time to intercept.

#### LOS Calculation

The following equation was used in calculating the change required in the ASAT seeker's LOS to center on and track the centroid:

$$\Delta \text{LOS} = a \frac{i_T(r_T)Q(\alpha)\alpha(t)}{i_T(r_T)Q(\alpha) + i_B(r_B)Q(\beta)} + b \frac{i_B(r_B)Q(\beta)\beta(t)}{i_T(r_T)Q(\alpha) + i_B(r_B)Q(\beta)} \quad (5.14)$$

where  $\Delta \text{LOS}$  = angle that the centroid is offset from the seeker LOS,

$a, b$  = weighting coefficients determined from ASAT weapon parameters,

$i_T, i_D$  = signals at output of seeker detector due to target ( $i_T$ ) and the balloon decoy ( $i_D$ ),

$r_T, r_D$  = distance from ASAT weapon to target ( $r_T$ ) and balloon decoy ( $r_D$ ),

$Q(\alpha), Q(\beta)$  = seeker off-axis response of target satellite [ $Q(\alpha)$ ] and balloon decoy [ $Q(\beta)$ ], at angles of  $\alpha$  and  $\beta$  from the ASAT LOS,

$\alpha(t)$  = angular displacement of target satellite from the ASAT LOS at time  $t$ , and

$\beta(t)$  = angular displacement of balloon decoy from the ASAT LOS at time  $t$ .

These relationships are illustrated in Figure 5-7. For centroid tracking, as assumed in this study, the constants  $a$  and  $b$  are both equal to one (39:33).

At each update cycle, the seeker will correct its LOS to the centroid of both sources (if both are still in its FOV) or to the single source (if the decoy or target is out of the FOV). The computer program must determine, after each update cycle, if the decoy is still in the FOV and whether the target satellite is hit. If the decoy leaves the field of view, the target is assumed to be hit. If both sources are within the FOV, to determine a hit, the program computes the ASAT-target distance when the difference between the x-components of their positions is less than 5 m (the diameter of both target and weapon). This follows from the description of both objects as spheres, and the definition of a hit as being a collision between the two.

The magnitude of the required velocity change is determined by the angular displacement of the centroid, as computed using equation 5.14,

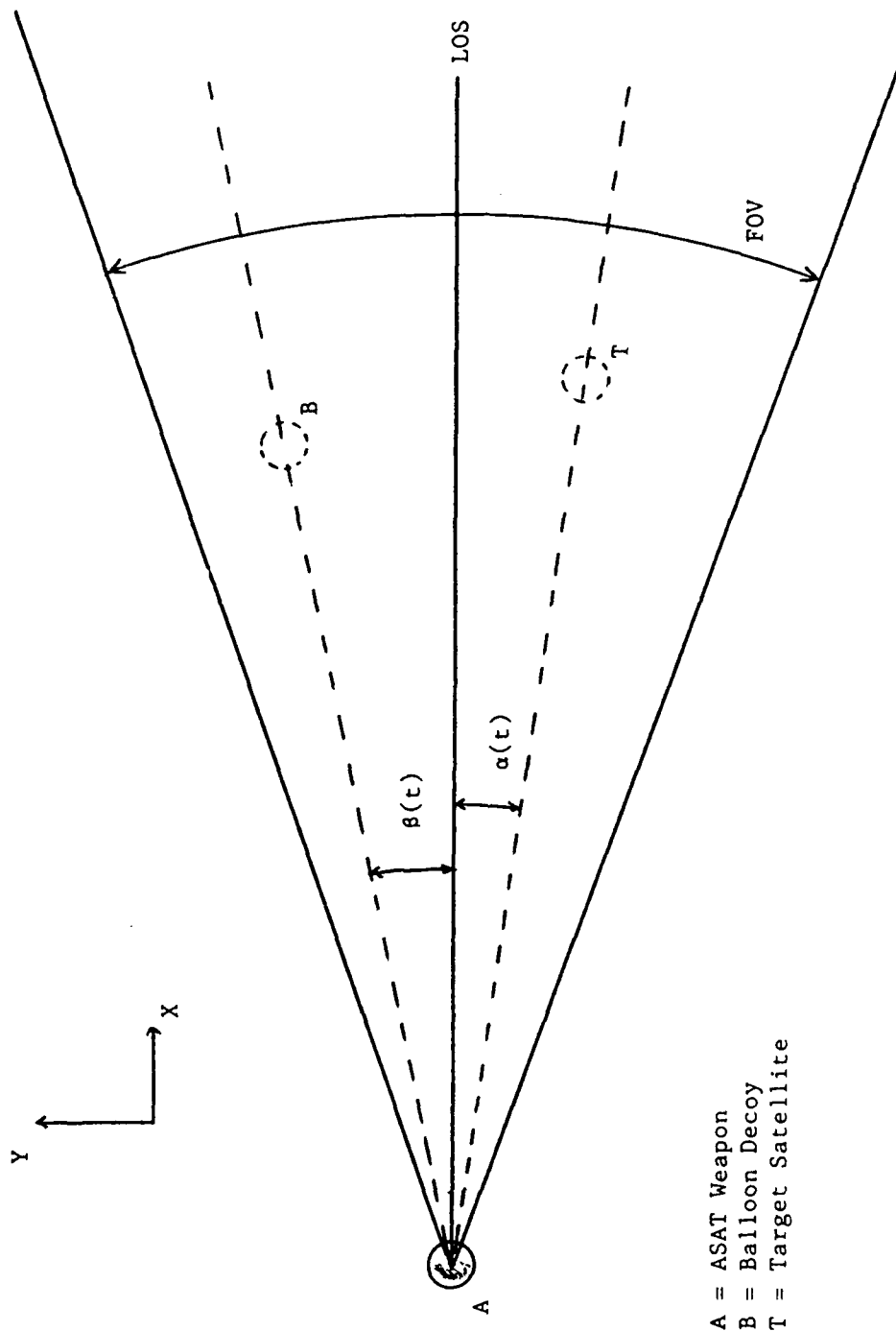


Figure 5-7. ASAT Seeker Field of View (FOV)

and the relative range and velocity data received by appropriate sensors assumed operating on the ASAT. The velocity change applied is the magnitude needed to move the ASAT a distance equal to the lateral displacement from the LOS at the target's range from the ASAT by the time another update cycle occurs. Since the angles are quite small, this distance equals the range times the angular displacement.

#### Program Decision Structure and Program Loop

The calculation of the positions and velocities of the three vehicles is performed by a complex decision structure. The salient portions of the decision flowchart are summarized in Figure 5-8.

A loop was added to the main program to provide data giving the minimum balloon-to-target (B/T) ratio needed to decoy the ASAT seeker. From a starting B/T ratio of 0.25 (i.e. balloon decoy intensity of 250 watts, target intensity of 1000 watts), the intensity of the balloon decoy is incremented 250 watts at a time, until the seeker is decoyed.

The validity of the computer program cannot be determined by direct comparison to real-world data, since an ASAT endgame at geosynchronous altitudes is currently only a theoretical exercise. As described in this chapter and Appendix A, the program components are written based on existing physical principles of astrodynamics, physics and infrared technology. As a result, it meets the criteria for axiomatic (or "a priori") validation, although the system analyzed herein does not exist today.

In addition, manual step-by step evaluation of the computer code, within limitations imposed by hand-held calculator accuracy supported

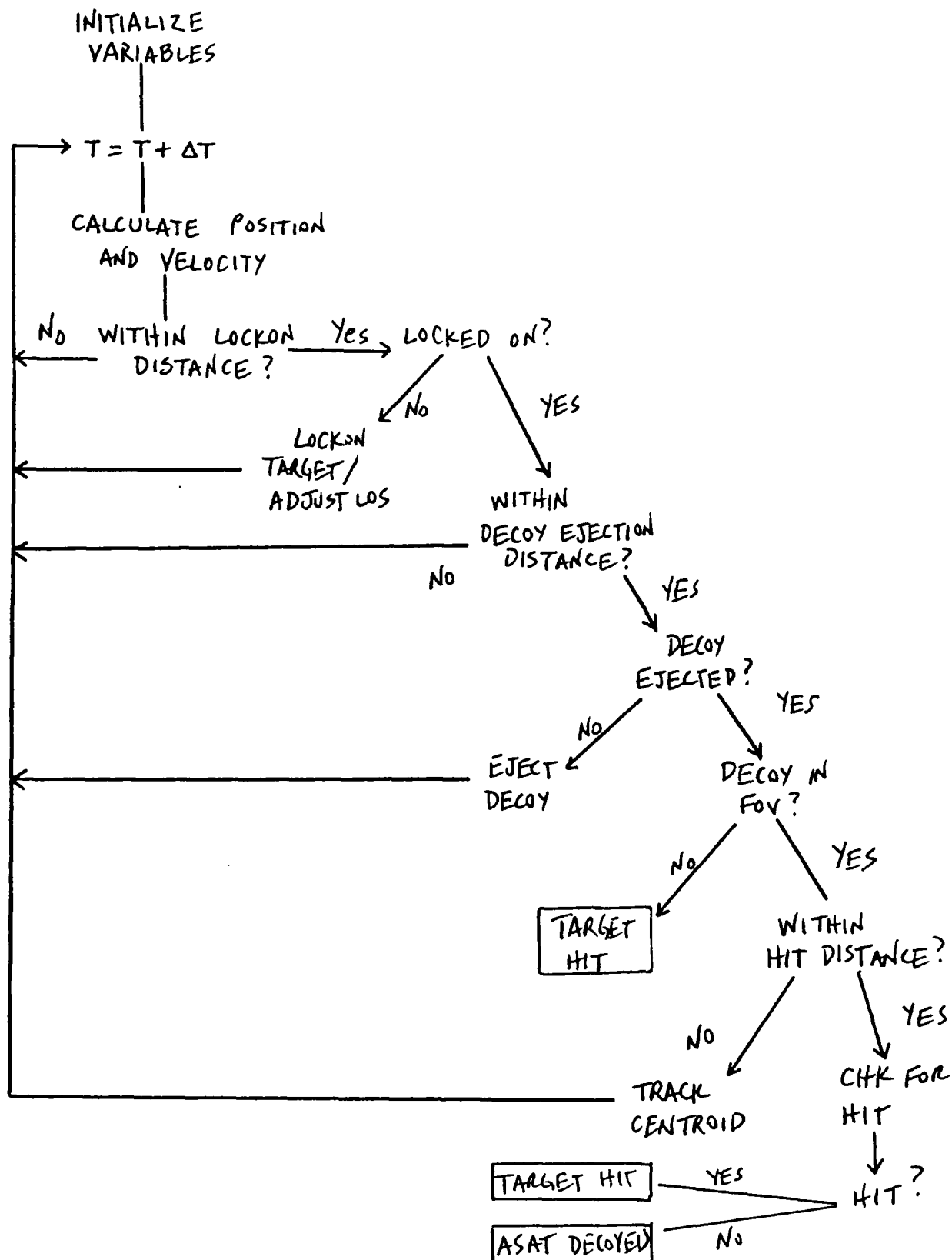


Figure 5-8. Decision Structure

the belief that the program performed as desired.

#### Analysis Method

The method of analysis used is to select nominal values of the parameters of interest---field of view, range at decoy ejection, ejection velocity of decoy and decoy ejection angle--- and to then vary each parameter from its nominal value.

The selected nominal values, when used together in an endgame, define a scenario whose end result is a target hit. Thus, successful decoy of the ASAT when a single parameter and the B/T ratio are varied, are consequences of only those two elements. The B/T ratios needed for a successful ASAT weapon decoy are plotted as a function of the varying parameter using a computer plotting package. The loop flow used in the program to produce the output data is illustrated in Figure 5-9. Table I lists the nominal parameter values used in this analysis.



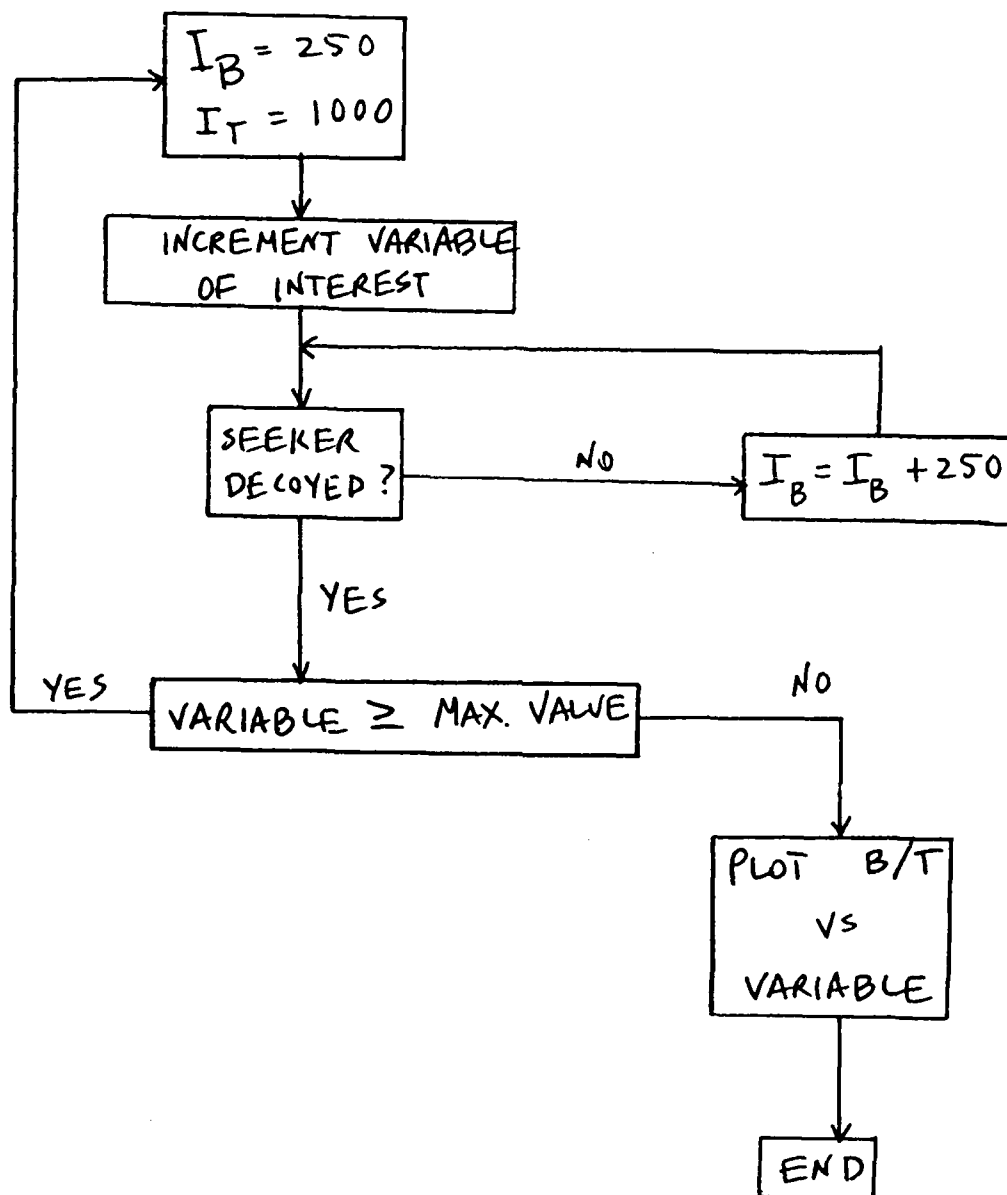


Figure 5-9. Loop Flow

Lockon Distance	460.0 km
Field of View	3.0 deg
Ejection Distance	100.0 km
Ejection Angle	0.2 rads
Ejection Velocity	1.0 m/sec
Seeker Damping Constant	10.5 milliradians

Table I. Nominal Parameter Values

## VI. Results

The four parameters of interest in this research---field of view of seeker, balloon decoy ejection velocity and ejection angle, and range at which the decoy was is ejected---were varied to examine the effect each would have on the Balloon-to-Target ratio needed to effectively decoy the ASAT weapon. A higher B/T ratio causes the centroid of the sources to move farther away from the target satellite. As the seeker tracks a point farther away from the target, the likelihood of the target colliding with the ASAT lessens. The results of this study appear as Figures 6-1, 6-2, 6-3 and 6-4.

Within the respective ranges of nominal values chosen, only three of the parameters affected the required B/T ratio needed to decoy the ASAT. Each of the parameters is discussed more fully below.

### Seeker Field of View (FOV)

Within the range of 0.5 to 3.0 degrees, the seeker field of view did not affect the level of the decoy's radiant intensity needed to decoy the ASAT. The B/T ratio required, when the remaining parameters were at their nominal values, remained constant over the whole range. The results of the computer program are graphed in Figure 6-4.

### Decoy Ejection Distance

The separation distance at the time of the decoy's ejection had some impact on the required B/T ratio to assure decoy of the ASAT. The results, graphed in Figure 6-2, indicate that a lower B/T ratio is

sufficient at greater distances. This seems contradictory, owing to the inverse square "fall-off" of radiation. However, it is feasible that the successful decoy of the ASAT with a lower B/T ratio occurs since, at greater decoy ejection distances, the decoy remains in the field of view longer, causing the seeker to "see" and correct to a position away from the target for a longer period of time. While the centroid is certainly closer to the real target when the B/T ratio is lower, the accumulation of many small off-axis errors by the seeker apparently contributes more than a higher ratio at smaller ranges.

#### Decoy Ejection Angle

The angle at which the balloon decoy is ejected is another parameter which greatly affected the B/T ratio required for a successful ASAT decoy. (See Figure 6-3.) Within a range of .75 - 1.5 radians, the B/T curve remained flat, but increased greatly as the ejection angle decreased. A smaller ejection angle places the balloon decoy's trajectory closer to that of the target vehicle, and the centroid of the two sources remains much closer to the target. As a result, the seeker will sense very small off-axis errors, and will not move out of the way of the approaching target satellite.

#### Decoy Ejection Velocity

The velocity at which the balloon decoy is ejected is another important factor. Since the seeker is tracking the centroid of the sources, if the centroid is moving rapidly away from the target, the

ASAT would quickly position itself away from the target, and possibly would lose it from the FOV.

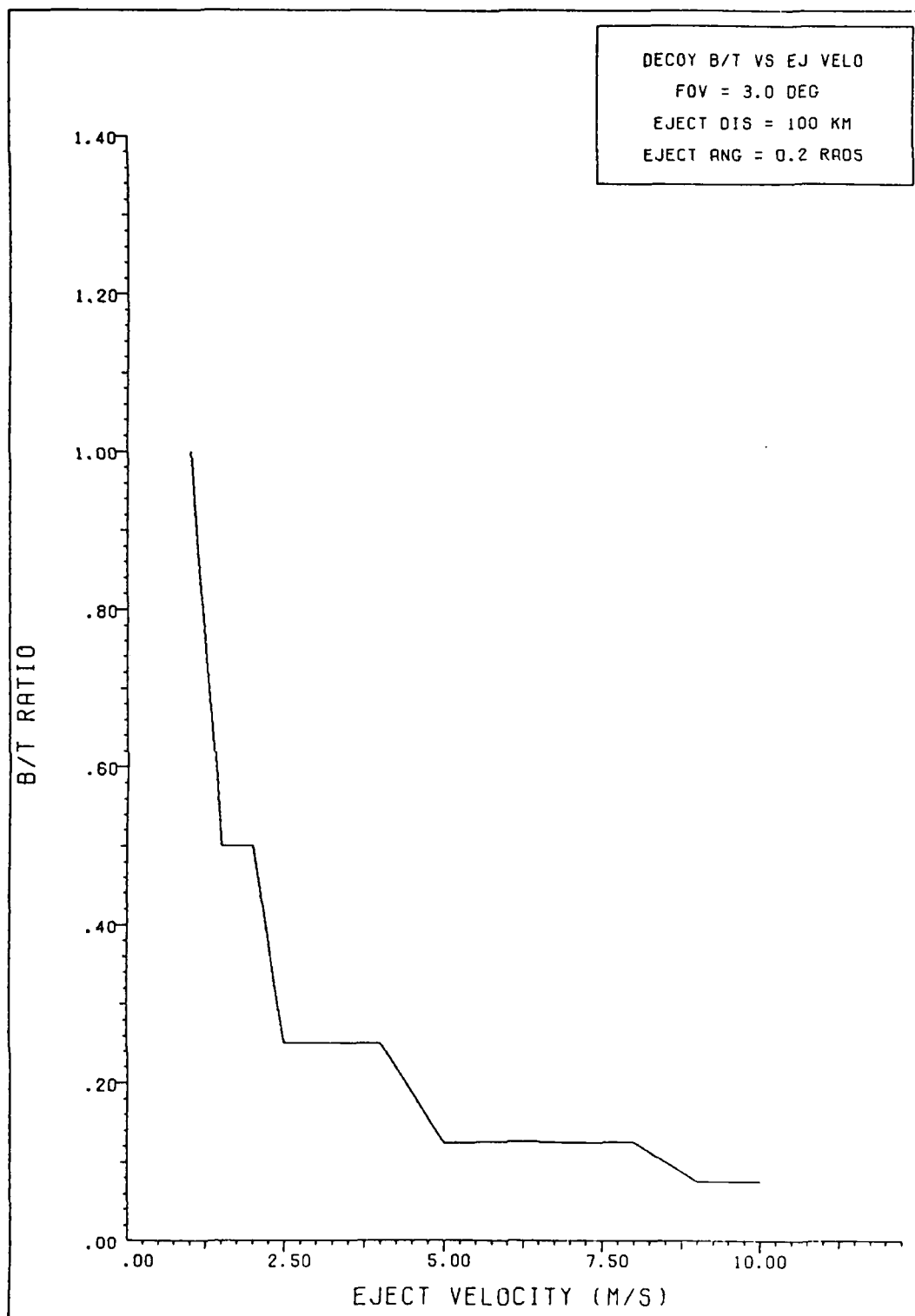


FIGURE 6-1. DECOY B/T RATIO (MINI) VS EJECTION VEL

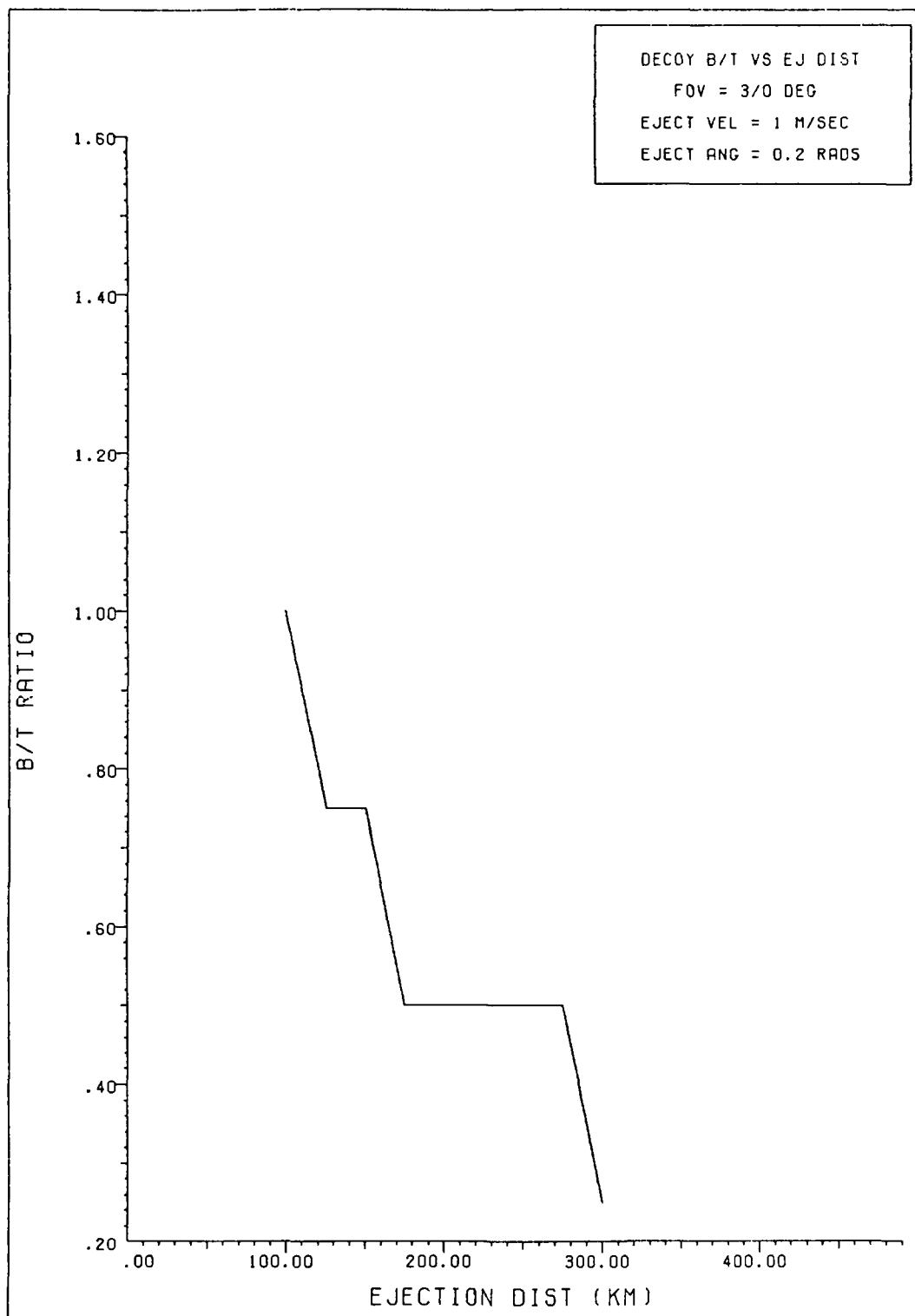


FIGURE 6-2. DECOY B/T RATIO (MIN) VS EJECTION

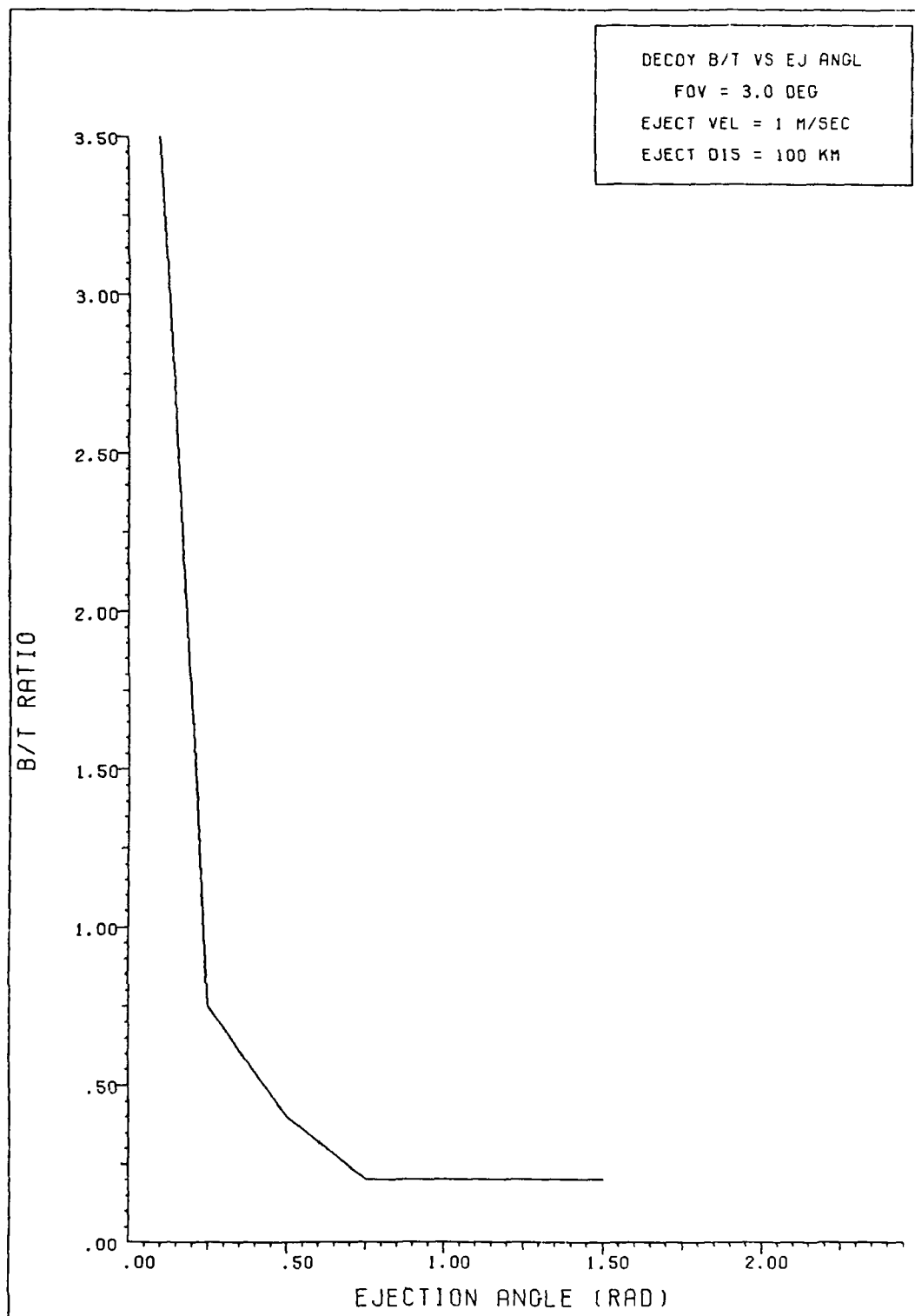


FIGURE 6-3. DECOY B/T RATIO (MIN) VS EJECT ANGLE



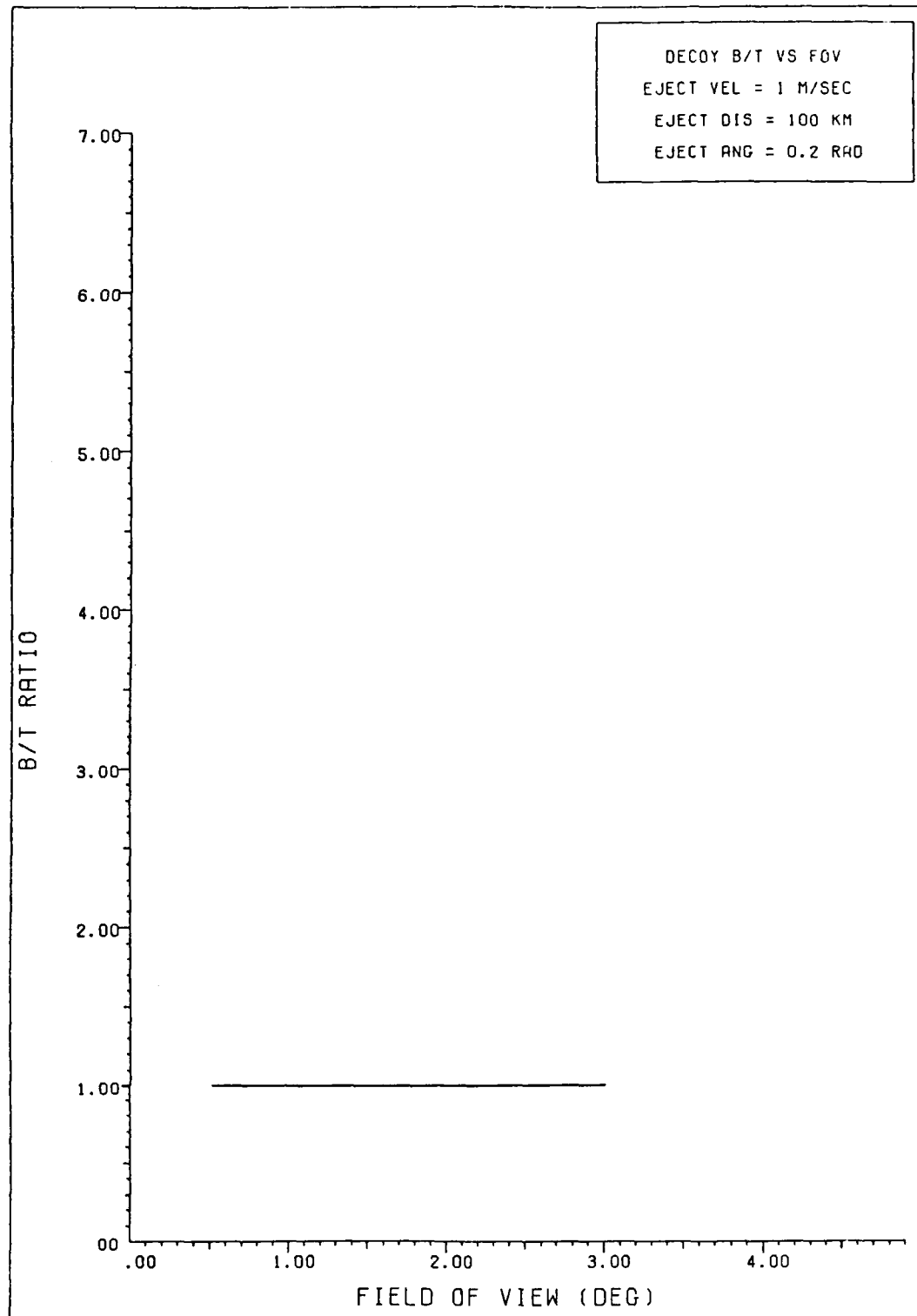


FIGURE 6-4. DECOY B/T (MIN) VS SEEKER FOV

## VII. Conclusions and Recommendations

Of the four parameters tested, only the field of view had a negligible effect on the minimum B/T ratio needed to decoy the ASAT weapon. The decoy ejection angle had little effect on the B/T ratio within a small range (.75 - 1.5 radians). The key parameters in the endgame encounter were the decoy ejection velocity and the distance at which the decoy was ejected from the target satellite.

The decoy ejection velocity is significant since it directly affects the lateral motion of the ASAT weapon away from the target vehicle. As the velocity increases (at a constant ejection angle and ejection distance), the "motion" of the centroid increases, causing the seeker guidance system to make greater changes in the ASAT's lateral movement. Ultimately, the ASAT is decoyed. One limiting factor, however, is the seeker update time. While higher ejection velocities seem to be more successful in causing a decoy of the ASAT, the velocity must remain small enough to permit the balloon decoy to remain in the seeker's FOV long enough to make the seeker see a centroid which is away from the target. If the velocity is too large, the balloon could be out of the FOV before the seeker sees two sources, resolved to a centroid, and corrects. Since the sole purpose of the balloon decoy is to avert destruction of the target satellite, it must remain in the FOV to create false data on which the seeker will act.

The distance at balloon ejection is another critical factor. If ejected at greater distances, the balloon will remain in the seeker's FOV for a longer period of time, and will provide false target data that much longer. The continuously-increasing balloon-target distance

causes the ASAT to correct to a point farther away from the target as the endgame continues. At shorter ejection distances, the ASAT is more likely to be hit by its target, since there is less time for the balloon-target distance (and hence, centroid-target distance) to increase. It is a situation on the order of "too little, too late" to accomplish as successful ASAT decoy. Limiting factors to increasing ejection distance are the intensities required to assure lockon by the seeker. Despite the data which suggested that the greater ejection distances are preferable, there is a limit to the distance at which the seeker can achieve a lockon. This is due to limitations on the sensitivity of the detector, as well as an increase in "noise" (i.e. non-target) sources as the tracking range increases.

Finally, the ejection angle is significant, if only as a lower bound on the ejection angles used. As the angle decreases, the required B/T ratio must increase to assure a successful decoy. This is required to force the seeker to track a centroid as close to the decoy as possible. Even at very high B/T ratios, there is a point at which the ejection angle is so small that the balloon-target separation is negligible, and the seeker will track a centroid between both sources which will cause the ASAT to collide with both the decoy and the target satellite.

#### Recommendations

The algorithm describing orbital motion, and used in this analysis, are relatively straightforward, but do entail a great deal of iterative calculations. As a result, the program, as written, taxes

computer resources a great deal. Owing to the reality of a geosynchronous ASAT threat in the future, a simplified model of the ASAT endgame at higher orbits would be beneficial, to prepare for the time when technology catches up to the problem, and a countermeasure against a geosynchronous ASAT attack is essential.

In addition, since very little research has been performed in this area, assumptions made during this analysis may be worthy of review as more information about potential ASAT systems becomes available. Thereafter, a repeat of this analysis, using real-time systems and capabilities, could provide data which could be verified, and incorporated into evolving ASAT defense systems.

## Appendix A

Newton's law of universal gravitation is the basis for celestial mechanics and astrodynamics. Simply stated, it says that every particle in the universe attracts every other particle with a force which is directly proportional to the product of the particles' masses and inversely proportional to the square of the distance between them. Thus for two particles separated by a distance  $r$ ,

$$F = G m_1 m_2 / r^2 \quad (A.1)$$

where  $F$  is the force of attraction,

$m_1$  and  $m_2$  are the masses, and

$G$  is the constant of gravitation (also called the universal gravitational constant (47:70)).

An orbiting earth satellite is thus acted upon by gravitational forces due to all other celestial particles. However, the dominant force on a satellite in earth orbit is that due to the earth, owing to its greater mass and proximity, relative to other celestial particles. The motion of an earth satellite may be quite accurately described by a two-body (i.e. earth and satellite) approximation of Newton's law of universal gravitation. In addition, in a two-body problem wherein one of the masses is much greater than the other, the smaller mass moves about the larger, and the solution of the earth/satellite two-body problem yields an orbital path which can be described by a conic section--- circle, ellipse, hyperbola or parabola (55:56,59; 40:82-85).

For the type of orbiting satellites considered in this analysis, the orbital paths are ellipses (for ASAT and decoy) and a circle (for the target satellite). (While mentioned separately, a circle is merely a special type of ellipse, with zero eccentricity.) Key terms used to describe elliptical orbits are as follows (See Figure A-1):

1. The earth is at one focus of the ellipse.
2. The point of closest approach to the earth is called perigee.
3. The point at which the object is farthest from the earth is apogee.
4. The major axis is a line joining the apogee and perigee. (More commonly, the orbit shape is described by half the length of the major axis, which is referred to as the semimajor axis and is denoted by the letter 'a'.)
5. The true anomaly, denoted by  $\theta$ , is the angle measured from the perigee to the position vector of the object. The origin of the angle is the focus of the ellipse where the earth is located.
6. The semi-latus rectum,  $p$ , is the magnitude of the position vector when the true anomaly is 90 degrees.
7. The eccentric anomaly,  $E$ , is formed by circumscribing a circle of radius 'a' about the ellipse and drawing a line from the circle, perpendicular to the major axis and passing through the position of the object on the ellipse.
8. The flight path angle,  $\beta$ , is the angle between the object's velocity vector and the "local horizon" (relative to earth) (5:9-12; 31:73).

In astronomy, the orbit and the position of a body which describe

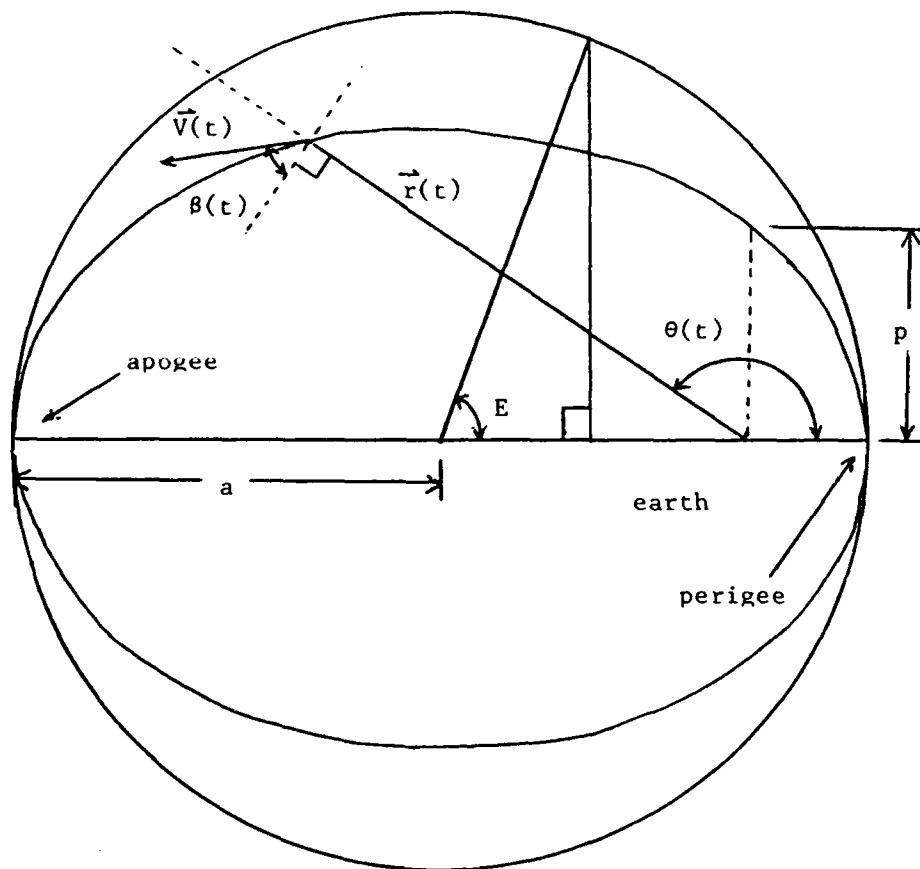


Figure A-1. Basic Earth Orbit Geometry

its orbit are defined by quantities called elements, some of which are mentioned above. Three of them define the orientation of the orbit with respect to a set of axes, two of them define the size and shape of the orbit, and the last element (with an associated time) defines the position of the body within the orbit at that time. Since the problem examined by this research assumed coplanar orbits for all bodies, and a coordinate system whose axes coincide with the major axis and semi-latus rectum of the ASAT's elliptical orbit, the first three elements were not needed to develop the problem solution. Nonetheless, for completeness here, the three elements are the longitude of the ascending node, the inclination of the orbit, and the longitude of perigee (47:22). A complete treatment of these elements is presented in basic astrodynamics texts, such as Refs. 4, 23, 31 and 47.

The two elements defining the size and shape of the orbit are the semimajor axis,  $a$  (described above), and the eccentricity,  $e$ . Eccentricity is a measure of an ellipse's "departure" from a circle. It is related to the distance of the focus of the ellipse from the center of the ellipse. The eccentricity is defined as this distance, divided by the length of the semimajor axis (47:23).

The final element is the time of perigee passage,  $\tau$ , which is a particular epoch when the body was at perigee. This time, together with any other selected time of interest, provides position information for the object at the time of interest.

An additional conclusion derived from the solution of the central force motion equation is that the angular momentum of the orbiting object remains constant in the absence of any force other than the



gravitational force of the earth. (A complete derivation of this relationship may be found in Ref 55, Chap 4 and Ref 47, Chap 4.) The angular momentum is defined by

$$h = r(t) v(t) \cos \beta(t) \quad (A.2)$$

where  $h$  is the angular momentum,

$r$  is the magnitude of the position vector (originating at earth's center),

$v$  is the magnitude of the object's velocity, and

$\beta$  is the flight path angle.

Since the radius vector turns through  $2\pi$  radians in the orbital period,  $T$ , the mean angular velocity (also known as the mean motion),  $n$ , is given by

$$n = 2\pi / T \quad (A.3)$$

If  $\tau$  is the time of perigee passage, the angle swept by a radius vector rotating about the focus with a mean angular velocity  $n$ , in an interval  $(t - \tau)$  will be  $M$ , where

$$M = n (t - \tau) \quad (A.4)$$

$M$ , as defined, is called the mean anomaly (47:84).

The eccentric anomaly,  $E$ , and the mean anomaly,  $M$ , are related by an equation called Kepler's Equation:

$$E - e \sin E = M \quad (A.5)$$

where  $e$  is the eccentricity. Combining Eqs. A.4 and A.5 yields the

equation

$$n(t - \tau) = E - e \sin E \quad (A.6)$$

which relates time to position in the orbit (47:84-86;31:35).

The various geometric relationships and equations used in the development of the computer program (in addition to those given above) are found in Table II. An explanation of their use in the program may be found in Chapter V. As described in that chapter, the initial velocity and distance from earth at burnout, together with the apogee and perigee distances, determine the remaining orbital elements. From those elements and the associated time, the position and velocity is calculated from values of orbital parameters at any time during the orbit.

Once the endgame commences (at most 4 minutes prior to apogee time for the ASAT weapon), any impulses applied to the ASAT will change its orbital elements. During the endgame, the lateral motion of the the weapon and target, relative to one another, is very small, so that impulses required to correct for this motion are also quite small, relative to the velocity of the ASAT weapon (approx 1 km/s). Since any impulses applied to the ASAT will lie within the same plane as the orbit (by definition), only the shape, not the orientation, of the ASAT's orbit will change. As you may recall, the orbit shape may be described completely by the eccentricity and length of the semimajor axis. The changes to these elements, due to an impulse, are given by

$$\Delta a = 2[(e \Delta v_s \sin \theta) + (p \Delta v_T / r)] / [n(1-e^2)]^{1/2} \quad (A.7)$$

$$\Delta e = (1-e^2)^{1/2} [(\Delta v_s \sin \theta) + \Delta v_T (\cos E + \cos \theta)] / na \quad (A.8)$$

where  $p$  is the semi-latus rectum ( $p = 1-e^2$ ),

$\Delta v_s$  is the impulse's velocity component along the position vector, and

$\Delta v_T$  is the component perpendicular to the position vector (47:253).

Computation of changes to these two elements yields new values for  $e$  and  $a$  which are used to determine the position and velocity of the ASAT weapon for later times. In like manner, subsequent impulses applied to the orbiting ASAT weapon produce additional changes to the eccentricity and semimajor axis, and describe a new orbit until another impulse is applied.

Element Relations for Burnout:

$$h = r_0 v_0 \cos \beta_0 = r_A v_A \quad (A.9)$$

$$r_0 = a(1-e^2) / (1 + e \cos \theta_0) \quad (A.10)$$

$$\cos E_0 = (e + \cos \theta_0) / (1 + e \cos \theta_0) \quad (A.11)$$

Element Relations During Enroute Times:

$$\tan[\theta(t)/2] = [(1 + e)/(1 - e)] \tan[E(t)/2] \quad (A.12)$$

$$\mu = G M_{\text{earth}} \quad (A.13)$$

$$\tan \beta(t) = [\mu r(t) e \sin \theta(t)] / h^2 \quad (A.14)$$

$$v(t) = \mu [(2/r(t) - (1/a)] \quad (A.15)$$

$$r(t) = [a(1 - e^2)] / [1 + e \cos \theta(t)] \quad (A.16)$$

$$p = a(1 - e^2) \quad (A.17)$$

$r_0$  = magnitude of position vector at burnout

$v_0$  = magnitude of velocity vector at burnout

$\beta_0$  = flight path angle at burnout

$r_A$  = magnitude of position vector at apogee

$v_A$  = magnitude of velocity vector at apogee

Table II. Orbital Equations

## Appendix B

A listing of the program developed and used to perform the analysis is given. In addition, a list of variables is provided.

### Variables

REARTH - radius of earth [km]  
RSYNC - distance of geosynchronous orbit from earth center [km]  
TSYNC - period of geosynchronous orbiting satellite [sec]  
RAPOG - apogee distance of ASAT orbit  
RPERIG - perigee distance of ASAT orbit  
HBURN - altitude of burnout [km]  
A - semi-major axis of ASAT orbit  
E - eccentricity of ASAT orbit  
VBURN - velocity of ASAT at burnout [km/s]  
RBURN - ASAT's distance from earth (center) at burnout [km]  
VAPOG - velocity of ASAT at orbit apogee [km/s]  
ANGMOM - angular momentum of ASAT  
TAPOG - time of apogee passage (measured from perigee) [sec]  
DDELTA - angular velocity of target [rads/sec]  
VSYNC - velocity of target  
DISEJK - range at which balloon is ejected [km]  
ANGEJK - angle (from target velocity) at which balloon ejected [rads]  
VELEJK - speed at which balloon is ejected [km/s]  
LOKDIS - lockon distance of ASAT [km]

DMPCON - seeker damping constant  
RELLIP - distance of ASAT from earth [km]  
VELLIP - velocity of ASAT [km/s]  
RELLX, RELLY - x,y components of RELLIP  
VELLX, VELLY - x,y components of VELLIP  
RCIRY - distance of target from earth [km]  
VCIRY - velocity of target [km/s]  
RCIRX, RCIRY - x,y components of RCIRY  
VCIRX, VCIRY - x,y components of VCIRY  
LOSLST - direction of LOS [= constant]  
LOSAT - line-of-sight between ASAT and Target  
LOSAB - line-of-sight between ASAT and Balloon  
LOSCEN - line-of-sight of centroid  
DISTAB - ASAT-Balloon distance [km]  
DISTAT - ASAT-Target distance [km]  
RBALLN - distance of balloon decoy from earth [km]  
VBALLN - velocity of balloon decoy [km/sec]  
RBALX, RBALY - x,y components of RBALLN  
VBALX, VBALY - x,y components of VBALLN  
I3AL - intensity of balloon decoy  
ITARG - intensity of target

#### Subroutine Orbinj

Given burnout parameters, and other physical constants, calculates the elements and parameters of the ASAT orbit.

#### Subroutine Setini

Sets time epoch as time from burnout and also translates this time to a time until intercept.

#### Subroutine Incrs

Sets the amount by which the time is incremented during the orbit calculations.

#### Subroutine Tarorb

Calculates the parameters for the target's orbit.

#### Subroutine Asafre

Calculates parameters of ASAT in its original (unperturbed) orbit, i.e. prior to lockon.

#### Subroutine Disvel

Calculates relative ranges and velocities of target and ASAT.

Subroutine Deltav

Calculates the required velocity change needed by the ASAT to center its LOS on the target or centroid.

Subroutine Asachg

Determines the elements of the ASAT orbit which results from an applied velocity change.

Subroutine Balejk

Calculates the parameters for the balloon decoy orbit from the time of its ejection.

Subroutine Balorb

Calculates the parameters of the balloon decoy orbit for the duration of the endgame.

Subroutine Centrd

Determines the location of the centroid.

Subroutine Chkhit

Determines if the target is hit.



```

PROGRAM ENGAME
DOUBLE PRECISION REARTH,RSYNC,MU,TSYNC,PI,RAPOG,RPERIG,HBURN,A,E,
*      VBURN,RBURN,VAPOG,ANGMOM,N,TAPOG,DDELTA,VSYN,
*      DISEJK,ANGEJK,VELEJK,LOKDIS,DMPCON,FOV,FVIEW,
*      BETA,THETA,PSI,TIME,DELTA,RELLX,RELLY,VELLX,
*      VELLY,RCIRX,RCIRY,VCIRX,VCIRY,DIST,VREL,LOS,
*      DIRVEL,INIDIS,INCR,RELLIP,VELLIP,LOSLST,
*      ANGOFF,DELTA,TIMAST,THETAS,THETCR,RBALLN,
*      RBALX,RBALY,VBALX,VBALY,VBALLN,TIBALN,BETBAL,
*      ABALLN,EBALLN,PSIBAL,THETEJ,NBALLN,DELTEJ,
*      THETBA,ALPHA,LOSAB,LOSAT,B.T,QB,QT,DISTAT,
*      DISTAB,BALCUR,TARCUR,LOSCEN,BTITS,IBAL,DISTBT,
*      LOSBT,BETAST,IBALLN,ITARG,DIAM,UPDATE,DEJ,AEJ,VEJ
*****
CHARACTER STATUS*16
*****
INTEGER ASAT,BALLOON,LOCKON,LINES,CYCLE
*****
OPEN (UNIT=4,FILE='TAPE5')
DO 32 FVIEW = 0.5,3.0,0.5
DO 30 DEJ = 100.,300.,50.
DO 28 AEJ = .10,1.5,.10
DO 26 VEJ = .001,.010,.001
DO 24 IBAL = 250.,3000.,250.
*****CONSTANTS
REARTH = 6378.165
RSYNC  = 42164.
MU      = 398602.8225
TSYNC   = 86164.
PI      = 3.1415926536
*****
***** ASAT ORBIT PARAMETERS (VEL=35000 F/S;ALT=400 NM @ BURNOUT)
RAPOG  = RSYNC
RPERIG = 2000.
HBURN  = 400.* 1.852
VBURN  = 35000. * .0003048
RBURN  = REARTH + HBURN
A      = (RAPOG + RPERIG)/2.
E      = (RAPOG - RPERIG)/(RAPOG + RPERIG)
VAPOG  = SQRT((MU*(1.-E))/(A*(1.+E)))
ANGMOM = RAPOG * VAPOG
N      = SQRT(MU/A**3)
TAPOG  = PI/N
THETCR = 0.
*****
***** TARGET ORBIT PARAMETERS
DDELTA = (2.*PI)/TSYNC
VSYN    = SQRT(MU/RSYN)
*****

```

\*\*\*\*\* ENDGAME PARAMETERS

DISEJK = DEJ  
 ANGEJK = AEJ  
 VELEJK = VEJ  
 DIAM = .005

\*\*\*\*\*

\*\*\*\*\* SENSOR PARAMETERS

LOKDIS = 460.  
 DMPCON = 10.5  
 FOV = FVIEW \* PI/180.  
 IBALLN = IBAL  
 ITARG = 1000.  
 LOSLST = PI/2.  
 CYCLE = 10

\*\*\*\*\*

\*\*\*\*\*

\*\*\*\*\*

```

      CALL ORBINJ (RAPOG,VAPOG,RBURN,VBURN,A,E,N,TAPOG,DDEL,RSYNC,PI,
*              VSYNC,BETA,THETA,PSI,TIME,DELT,RELLX,RELLY,VELLX,
*              VELLY,RCIRX,RCIRY,VCIRX,VCIRY,DIST,VREL,LOS,DIRVEL,
*              RELIP,ASAT,BALON,INIDIS,LOCKON,VELIP,STATUS)
      CALL PRNTOP (BETA,PI,RPERIG,RAPOG,E,TAPOG,TIME,DISEJK,VELEJK,
*              ANGEJK,LOKDIS,DMPCON,FOV,BTITS,IBALLN,ITARG)
      CALL PRNHDR (LINES)
      CALL PDATA1 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSYNC,VCIRX,
*              VCIRY,THETA,BETA,E,PSI,A,RELIP,RELLX,RELLY,VELIP,
*              VELLX,VELLY,DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS)
      CALL SETINI (TAPOG,TIME)
20    CALL INCRS (DIST,INIDIS,TIME,INCR)
      CALL TARORB (TAPOG,TIME,DDEL,DELT,VCIRX,VCIRY,RCIRX,RCIRY,
*              VSYNC,RSYNC)
      IF (ASAT .EQ. 0) THEN
        CALL ASAFRE (N,TIME,PSI,E,A,MU,THETA,RELIP,BETA,VELIP,
*              RELX,RELLY,VELLX,VELLY)
        CALL DISVEL (RCIRX,RELLX,RCIRY,RELLY,VCIRX,VELLX,VCIRY,
*              VELLY,PI,DIST,VREL,LOS,DIRVEL)
      IF (LOCKON .EQ. 0) THEN
        IF (DIST .LE. LOKDIS) THEN
          LOCKON = 1
          UPDATE = 0
          IF ((ABS(LOS-LOSLST)) .LE. (1E-9)) THEN
            STATUS = 'INITIAL LOCKON'
            CALL PDATA1 (LINES,STATUS,DELT,RSYNC,RCIRX,
*              RCIRY,VSYNC,VCIRX,VCIRY,THETA,BETA,
*              PSI,A,RELIP,RELLX,RELLY,VELIP,
*              VELLX,VELLY,DIST,VREL,DIRVEL,LOS,
*              TIME,TAPOG,BTITS)

```

```

ELSE
  STATUS = 'INIT LOCK/LOSADJ'
  ANGOFF = LOSLST - LOS
  CALL DELTAV (ANGOFF,DIST,DELV,CYCLE)
  IF (ABS(DELV) .LT. (1E-4)) THEN
    DEL = 0.
    CALL PDATA2 (LINES,STATUS,DELT,RSYNC,RCIRX,
      RCIRY,VSINC,VCIRX,VCIRY,THETA,BETA,
      PSI,A,RELLIP,RELLX,RELLY,VELLIP,
      VELLX,VELLY,DIST,VREL,DIRVEL,LOS,
      TIME,TAPOG,BTITS,DELV)
  ELSE
    CALL PDATA2 (LINES,STATUS,DELT,RSYNC,RCIRX,
      RCIRY,VSINC,VCIRX,VCIRY,THETA,BETA,
      PSI,A,RELLIP,RELLX,RELLY,VELLIP,
      VELLX,VELLY,DIST,VREL,DIRVEL,LOS,
      TIME,TAPOG,BTITS,DELV)
    CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,
      ASAT,TIMAST,THETAS,THETCR,BETAST,
      RELLX,RELLY)
  END IF
END IF
ELSE
  STATUS = 'FREEFLIGHT'
END IF
ELSE
  IF (BALOON .EQ. 0) THEN
    IF (DIST .GT. DISEJK) THEN
      STATUS = 'TARGET LOCKON'
      IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
      ELSE
        UPDATE = 0
        ANGOFF = LOSLST - LOS
        CALL DELTAV (ANGOFF,DIST,DELV,CYCLE)
        IF (ABS(DELV) .LT. (1E-4)) THEN
          DELV = 0.
        ELSE
          CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,
            MU,ASAT,TIMAST,THETAS,THETCR,BETAST,
            RELLX,RELLY)
        END IF
      END IF
    ELSE
      STATUS = 'DEPLOY BALLOON'
      CALL BALEJK (RSYNC,RCIRX,RCIRY,DELT,VELEJK,ANGEJK,
        VCIRX,VCIRY,MU,RBALLN,RBALX,RBALY,VBALX,
        VBALY,VBALLN,BALOON,TIBALN,BETBAL,
        ABALLN,EBALLN,PSIBAL,THETEJ,NBALLN,
        DELTEJ)
    END IF
  END IF

```

```

      IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
        CALL PDATA3 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
*          VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
*          RELIP,RELLX,RELLY,VELLIP,VELLX,VELLY,
*          DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,
*          THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,
*          RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY)
      ELSE
        UPDATE = 0
        ANGOFF = LOSLST - LOS
        CALL DELTAV (ANGOFF,DIST,DELV,CYCLE)
        IF (ABS(DELV) .LT. (1E-4)) THEN
          DELV = 0.
          CALL PDATA4 (LINES,STATUS,DELT,RSYNC,RCIRX,
*            RCIRY,VSYNC,VCIRX,VCIRY,THETA,
*            BETA,E,PSI,A,RELIP,RELLX,RELLY,
*            VELLIP,VELLX,VELLY,DIST,VREL,
*            DIRVEL,LOS,TIME,TAPOG,BTITS,
*            THETEJ,BETBAL,EBALLN,PSIBAL,
*            ABALLN,RBALLN,RBALX,RBALY,VBALLN,
*            VBALX,VBALY,DELV)
        ELSE
          CALL PDATA4 (LINES,STATUS,DELT,RSYNC,RCIRX,
*            RCIRY,VSYNC,VCIRX,VCIRY,THETA,
*            BETA,E,PSI,A,RELIP,RELLX,RELLY,
*            VELLIP,VELLX,VELLY,DIST,VREL,
*            DIRVEL,LOS,TIME,TAPOG,BTITS,
*            THETEJ,BETBAL,EBALLN,PSIBAL,
*            ABALLN,RBALLN,RBALX,RBALY,VBALLN,
*            VBALX,VBALY,DELV)
          CALL ASACHG (DELV,THETA,PI,A,E,RELIP,N,PSI,
*            MU,ASAT,TIMAST,THETAS,THETCR,
*            BETAST,RELLX,RELLY)
        END IF
      END IF
    ELSE
      STATUS = 'TRACK CENTROID'
      CALL BALORB (TIBALN,INCR,NBALLN,PSIBAL,EBALLN,ABALLN,
*        MU,DELTEJ,THETEJ,PI,THETBA,RBALLN,BETBAL,
*        VBALLN,RBALX,RBALY,VBALX,VBALY)
      CALL DISLOS (DIST,RBALX,RELLX,RBALY,RELLY,PI,RCIRX,
*        RCIRY,LOSAB,LOSAT,LOSBT,DISTAB,DISTAT,
*        DISTBT,LOS)
      IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
        IF (RCIRX .GT. RELX) THEN
          IF ((RCIRX - RELX) .LT. DIAM) THEN
            CALL CHKHIT (DISTAT,DIAM,RCIRX,RELLX,STATUS)
          
```

```

      CALL PDATA5 (LINES,STATUS,DELT,RSYNC,RCIRX,
*          RCIRY,VSINC,VCIRX,VCIRY,THETA,BETA,
*          E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,
*          VELLX,VELLY,DISTAT,VREL,DIRVEL,
*          LOSAT,TIME,TAPOG,BTITS,THETBA,
*          BETBAL,EBALLN,PSIBAL,ABALLN,RBALLN,
*          RBALX,VBALY,VBALLN,VBALX,VBALY,
*          DISTAB,DISTBT,LOSAB,LOSBT)
      IF (STATUS .NE. 'TARGET HIT') THEN
        GO TO 26
      END IF
    END IF
  END IF
ELSE
  UPDATE = 0
  CALL ANGLE (DISTAT,DISTAB,DISTBT,LOSAT,LOSAB,LOSBT,
*          LOSLST,ALPHA,B,T)
  CALL RSPONS (B,QB,DMPCON)
  CALL RSPONS (T,QT,DMPCON)
  CALL SNSOUT (QB,IBALLN,DISTAB,BALCUR)
  CALL SNSOUT (QT,ITARG,DISTAT,TARCUR)
  CALL CENTRD (B,FOV,T,LOSLST,LOSAT,LOSAB,ALPHA,
*          BALCUR,TARCUR,DISTAT,VREL,PI,DIRVEL,
*          STATUS,LOSCEN,ANGOFF,DISTAB,CYCLE)
  IF (RCIRX .GT. RELLX) THEN
    IF ((RCIRX - RELLX) .LT. DIAM) THEN
      CALL CHKHIT (DISTAT,DIAM,RCIRX,RELLX,STATUS)
      CALL PDATA5 (LINES,STATUS,DELT,RSYNC,RCIRX,
*          RCIRY,VSINC,VCIRX,VCIRY,THETA,
*          BETA,E,PSI,A,RELLIP,RELLX,RELLY,
*          VELLIP,VELLX,VELLY,DISTAT,VREL,
*          DIRVEL,LOSAT,TIME,TAPOG,BTITS,
*          THETBA,BETBAL,EBALLN,PSIBAL,
*          ABALLN,RBALLN,RBALX,VBALY,VBALLN,
*          VBALX,VBALY,DISTAB,DISTBT,LOSAB,
*          LOSBT)
      IF (STATUS .NE. 'TARGET HIT') THEN
        GO TO 26
      END IF
    END IF
  END IF
  CALL DELTAV (ANGOFF,DISTAT,DELV,CYCLE)
  IF (ABS(DELV) .LT. (1E-4)) THEN
    DELV = 0.
  ELSE
    CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,
*          ASAT,TIMAST,THETAS,THETCR,BETAST,
*          RELLX,RELLY)
  END IF
END IF
END IF
END IF

```

```

ELSE
  CALL ASAORB (TIMAST,INCR,N,E,PSI,A,MU,THETCR,THETA,RELLIP,
*          BETA,VELLIP,RELLX,RELLY,VELLX,VELLY,PI)
  CALL DISVEL (RCIRX,RELLX,RCIRY,RELLY,VCIRX,VELLX,VCIRY,
*          VELLY,PI,DIST,VREL,LOS,DIRVEL)
  IF (BALOON .EQ. 0) THEN
    IF (DIST .GT. DISEJK) THEN
      STATUS = 'TARGET LOCKON'
      IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
      ELSE
        UPDATE = 0
        ANGOFF = LOSLST - LOS
        CALL DELTAV (ANGOFF,DIST,DELV,CYCLE)
        IF (ABS(DELV) .LT. (1E-4)) THEN
          DELV = 0.
        ELSE
          CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,
*          ASAT,TIMAST,THETAS,THETCR,BETAST,
*          RELX,RELY)
        END IF
      END IF
    ELSE
      STATUS = 'DEPLOY BALLOON'
      CALL BALEJK (RSYNC,RCIRX,RCIRY,DELT,VELEJK,ANGEJK,
*          VCIRX,VCIRY,MU,RBALLN,RBALX,RBALY,VBALX,
*          VBALY,VBALLN,BALOON,TIBALN,BETBAL,ABALLN,
*          EBALLN,PSIBAL,THETEJ,NBALLN,DELTEJ)
      IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
        CALL PDATA3 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
*          VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
*          RELX,RELY,VELLIP,VELLX,VELLY,
*          DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,
*          THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,
*          RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY)
      ELSE
        UPDATE = 0
        ANGOFF = LOSLST - LOS
        CALL DELTAV (ANGOFF,DIST,DELV,CYCLE)
        IF (ABS(DELV) .LT. (1E-4)) THEN
          DELV = 0.
          CALL PDATA4 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
*          VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
*          RELX,RELY,VELLIP,VELLX,VELLY,
*          DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,
*          THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,
*          RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY,
*          DELV)

```

```

ELSE
    CALL PDATA4 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
*           VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
*           RELIP,RELLX,RELLY,VELLIP,VELLX,VELLY,
*           DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,
*           THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,
*           RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY,
*           DELV)
    CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,
*           ASAT,TIMAST,THETAS,THETCR,BETAST,
*           RELX,RELLY)
    END IF
    END IF
    END IF
ELSE
    STATUS = 'TRACK CENTROID'
    CALL BALORB (TIBALN,INCR,NBALLN,PSIBAL,EBALLN,ABALLN,MU,
*           DELTEJ,THETEJ,PI,THETBA,RBALLN,BETBAL,VBALLN,
*           RBALX,RBALY,VBALX,VBALY)
    CALL DISLOS (DIST,RBALX,RELLX,RBALY,RELLY,PI,RCIRX,RCIRY,
*           LOSAB,LOSAT,LOSBT,DISTAB,DISTAT,DISTBT,LOS)
    IF ((NINT(UPDATE)) .LT. CYCLE) THEN
        UPDATE = UPDATE + INCR
        IF (RCIRX .GT. RELX) THEN
            IF ((RCIRX-RELLX) .LT. DIAM) THEN
                CALL CHKHIT (DISTAT,DIAM,RCIRX,RELLX,STATUS)
                CALL PDATA5 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
*           VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
*           RELIP,RELLX,RELLY,VELLIP,VELLX,VELLY,
*           DISTAT,VREL,DIRVEL,LOSAT,TIME,TAPOG,
*           BTITS,THETBA,BETBAL,EBALLN,PSIBAL,
*           ABALLN,RBALLN,RBALX,RBALY,VBALLN,VBALX,
*           VBALY,DISTAB,DISTBT,LOSAB,LOSBT)
                IF (STATUS .NE. 'TARGET HIT') THEN
                    GO TO 26
                END IF
            END IF
        END IF
    END IF
    END IF
    END IF
ELSE
    UPDATE = 0
    CALL ANGLE (DISTAT,DISTAB,DISTBT,LOSAT,LOSAB,LOSBT,
*           LOSLST,ALPHA,B,T)
    CALL RSPONS (R,QB,DMPCON)
    CALL RSPONS (T,QT,DMPCON)
    CALL SNSOUT (QB,IBALLN,DISTAB,BALCUR)
    CALL SNSOUT (QT,ITARG,DISTAT,TARCUR)
    CALL CENTRD (B,FOV,T,LOSLST,LOSAT,LOSAB,ALPHA,
*           BALCUR,TARCUR,DISTAT,VREL,PI,DIRVEL,
*           STATUS,LOSCEN,ANGOFF,DISTAB,CYCLE)

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      IF (RCIRX .GT. RELX) THEN
        IF ((RCIRX - RELX) .LT. DIAM) THEN
          CALL CHKHIT (DISTAT,DIAM,RCIRX,RELLX,STATUS)
          CALL PDATA5 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,
            *          VSYNC,VCIRX,VCIRY,THETA,BETA,E,PSI,A,
            *          RELX,RELLX,RELLY,VELLIP,VELLX,VELLY,
            *          DISTAT,VREL,DIRVEL,LOSAT,TIME,TAPOG,
            *          BTITS,THETBA,BETBAL,EBALLN,PSIBAL,
            *          ABALLN,RBALLN,RBALX,RBALY,VBALLN,VBALX,
            *          VBALY,DISTAB,DISTBT,LOSAB,LOSBT)
          IF (STATUS .NE. 'TARGET HIT') THEN
            GO TO 26
          END IF
        END IF
      END IF
    END IF
  END IF
  CALL DELTAV (ANGOFF,DISTAT,DELV,CYCLE)
  IF (ABS(DELV) .LT. (1E-4)) THEN
    DELV = 0.
  ELSE
    CALL ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,
      *          ASAT,TIMAST,THETAS,THETCR,BETAST,
      *          RELX,RELLY)
    END IF
  END IF
END IF
END IF
END IF
IF (RCIRX .GT. RELX) THEN
  IF (LINES .GE. 61) THEN
    CALL PRNHDR (LINES)
  END IF
  GO TO 20
END IF
24 CONTINUE
26 CONTINUE
28 CONTINUE
30 CONTINUE
32 CONTINUE
CLOSE (4)
END
*****
*****
*****
SUBROUTINE ORBINJ (RAPOG,VAPOG,RBURN,VBURN,A,E,N,TAPOG,DDELT,
*          RSYNC,PI,VSYNC,BETA,THETA,PSI,TIME,DELT,
*          RELX,RELLY,VELLX,VELLY,RCIRX,RCIRY,VCIRX,
*          VCIRY,DIST,VREL,LOS,DIRVEL,RELLIP,ASAT,
*          BALOON,INIDIS,LOCKON,VELLIP,STATUS)
  INTEGER ASAT,BALOON,LOCKON
  DOUBLE PRECISION RAPOG,VAPOG,RBURN,VBURN,A,E,N,TAPOG,DDELT,
*          RSYNC,PI,VSYNC,BETA,THETA,PSI,TIME,DELT,RELLX,
*          RELLY,VELLX,VELLY,RCIRX,RCIRY,VCIRX,VCIRY,
*          DIST,VREL,LOS,DIRVEL,INIDIS,RELLIP,VELLIP

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CHARACTER STATUS*16
RELLIP = RBURN
BETA = ACOS((RAPOG*VAPOG)/(RBURN*VBURN))
THETA = ACOS((((A*(1.-E**2))/RBURN)-1.)/E)
PSI = ACOS((A-RBURN)/(A*E))
TIME = (PSI-E*SIN(PSI))/N
DELT = (TAPOG-TIME)*DDELT
RELLX = RBURN*SIN(THETA)
RELLY = -RBURN*COS(THETA)
VELLX = VBURN*COS(THETA-BETA)
VELLY = VBURN*SIN(THETA-BETA)
RCIRX = RSYNC*SIN(DELT)
RCIRY = RSYNC*COS(DELT)
VELLIP = VBURN
VCIRX = -VSYNC*COS(DELT)
VCIRY = VSYNC*SIN(DELT)
DIST = SQRT((RCIRX-RELLX)**2 + (RCIRY-RELLY)**2)
VREL = SQRT((VCIRX-VELLX)**2 + (VCIRY-VELLY)**2)
LOS = ATAN((RCIRX-RELLX)/(RCIRY-RELLY))
IF (LOS .LT. 0.) THEN
    LOS = PI + LOS
END IF
DIRVEL = ATAN((VELLX-VCIRX)/(VELLY-VCIRY))
IF (DIRVEL .LT. 0) THEN
    DIRVEL = PI + DIRVEL
END IF
STATUS = 'BURNOUT CONDIT'
ASAT = 0
BALOON = 0
LOCKON = 0
INIDIS = DIST
END

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SUBROUTINE PRNTOP (BETA,PI,RPERIG,RAPOG,E,TAPOG,TIME,DISEJK,
*                 VELEJK,ANGEJK,LOKDIS,DMPCON,FOV,BTITS,
*                 IBALLN,ITARG)
DOUBLE PRECISION BETA,PI,RPERIG,RAPOG,E,TAPOG,TIME,DISEJK,
*                 VELEJK,ANGEJK,LOKDIS,DMPCON,FOV,BETADG,
*                 TAUSEC,TAUMIN,TAUHRS,BTITS,BTITM,BTITH,
*                 FOVMRD,FOVDEG,IBALLN,ITARG
REAL BFPAR,BFPADG,OP,OA,ECCEN,OPERIS,OPERIM,OPERIH,RBTITS,
*   RBTITM,RBTITH,RDISEJ,RVELEJ,RANGEJ,RLOKDI,RDMPCO,
*   RFOVDE,RFOVMR,IRATIO
BETADG = BETA * 180./PI
TAUSEC = 2. * TAPOG
TAUMIN = TAUSEC/60.
TAUHRS = TAUSEC/3600.
BTITS = TAPOG - TIME
BTITM = BTITS/60.
BTITH = BTITS/3600.

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FOVDEG = FOV * 180./PI
FOVMRD = FOV * 1000.
BFPAR = BETA
BFPADG = BETADG
OP      = RPERIG
OA      = RAPOG
ECCEN   = E
OPERIS  = TAUSEC
OPERIM  = TAUMIN
OPERIH  = TAUHRS
RBTITS  = BTITS
RBTITM  = BTITM
RBTITH  = BTITH
RDISEJ  = DISEJK
RVELEJ  = VELEJK
RLOKDI  = LOKDIS
RDMPCO  = DMPCON
RFOVDE  = FOVDEG
RFOVMR  = FOVMRD
RANGEJ  = ANGEJK
IRATIO  = IBALLN/ITARG
WRITE (4,600)
WRITE (4,605) BFPAR,BFPADG
WRITE (4,610) OP.OA,ECCEN,OPERIS,OPERIM,OPERIH,RBTITS,RBTITM,
*           RBTITH
WRITE (4,615) RDISEJ,RVELEJ,RANGEJ
WRITE (4,620) RLOKDI,RDMPCO,RFOVDE,RFOVMR
WRITE (4,625) IRATIO
600  FORMAT (' **** APOGEE INTERCEPT ASAT ENDGAME AT',
*          ' GEOSYNCHRONOUS ORBIT **** '/' ASAT ORBIT:')
605  FORMAT ('      BURNOUT ALTITUDE (KM) = 740.8000016 (= 400 NM)'/
*          '      BURNOUT VELOCITY (KM/S) = 10.668 (= 15000 FT/S)'/
*          '      BURNOUT FLT PATH ANGLE = '.F8.5,' RADS (= '.F8.5,
*          ' DEG)')
610  FORMAT ('      ORBIT PERIGEE (KM) = ',F9.2/
*          '      ORBIT APOGEE (KM) = ',F9.2/
*          '      ECCENTRICITY          = ',F10.8/
*          '      ORBIT PERIOD          = '.F10.3.' SEC (= '.F9.3,
*          ' MIN = ',F9.5.' HRS)'/
*          '      BURNOUT-TO-INTERCEPT TIME = '.F10.3.' SEC (= '.
*          ' F9.3,' MIN = ',F9.5.' HRS)')
615  FORMAT ('      BALLOON DECOY: '/
*          '      RANGE AT EJECTION (KM) = ',F7.2/
*          '      EJECTION VELOCITY (KM/S) = ',F7.4/
*          '      EJECTION ANGLE (RADS)   = '.F7.4,
*          ' (FROM DIRECTION OF TARGET VELOCITY)')
620  FORMAT ('      SENSOR: '/
*          '      LOCK-ON DIST (KM) = '.F8.3/
*          '      DAMPING CONSTANT (MRADS) = '.F7.3/
*          '      FIELD OF VIEW = ',F5.2,' DEG (= ',F7.3,
*          ' MILLIRADS)')

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625  FORMAT ('  RATIO OF INTENSITIES (BALLOON-TO-TARGET) = ',
*      F7.3//)
      END
*****
*****
*****
      SUBROUTINE PRNHDR (LINES)
      INTEGER LINES
      CHARACTER AP*4,WP*7,TP*6,VP*8,BP*7,DP*6,DLP*14,ATP*11,AWP*11,
*          TIP*4,THP*5,BEP*4,EP*1,DEP*5,PSP*3,FP*5,RP*5,VKMP*7,
*          TVP*14,RXP*4,RYP*4,VXP*4,VYP*4,BOP*7,MIP*5,RA*5,KMSP*6,
*          ENP*14,KP*4,RELP*6,DIRP*7,DVP*6,AKP*5,ABP*12,TBP*14,
*          BDP*13,TO*3,INTCP*6,TFB*9,TTI*7
      VP=' VEHICLE'
      AP=' ASAT'
      WP=' WEAPON'
      TP=' TARGET'
      BP=' BALLOON'
      DP=' DECOY'
      DLP=' DISTANCE / LOS'
      ATP=AP//'- '//TP
      AWP=AP//WP
      BDP=BP//DP
      TIP=' TIME'
      THP=' THETA'
      BEP=' BETA'
      EP=' E'
      DEP=' DELTA'
      PSP=' PSI'
      FP=' FROM'
      RP=' R(KM)'
      VKMP=' V(KM/S)'
      TVP=TP//VP
      RXP=' R(X)'
      RYP=' R(Y)'
      VXP=' V(X)'
      VYP=' V(Y)'
      AKP=' A(KM)'
      DIRP=' DIRRELV'
      RELP=' RELVEL'
      BOP=' BURNOUT'
      MIP=' (MIN)'
      RA=' (RAD)'
      KMSP=' (KM/S)'
      ENP=' ENDGAME STATUS'
      KP=' (KM)'
      DVP=' DELTAV'
      ABP=AP//'- '//BP
      TBP=TP//'- '//BP
      TFB=TIP//FP
      TO=' TO'
      INTCP=' INTCP'

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```

TTI=TIP//TO
WRITE (4,698)
WRITE (4,700) TFB,AWP,TVP,BDP,DLP,ATP
WRITE (4,705) BOP,PSP,BEP,EP,DEP,PSP,BEP,EP,KP,RA.RELP,DIRP
WRITE (4,710) THP,DVP,AKP,THP,AKP,KMSP.RA
WRITE (4,715) TTI.RP,VKMP.RP,VKMP.RP,VKMP.ATP
WRITE (4,720) INTCP,RXP,VXP,RXP,VXP,RXP,VXP,ABP
WRITE (4,725) MIP,RYP,VYP,RYP.VYP.RYP.VYP.TBP.ENP
WRITE (4,730)
698 FORMAT ('1',128('-'))
700 FORMAT (1X,A9,7X,A11,13X,A14,13X,A13,11X,A14,9X,A11)
705 FORMAT (2X,A7,2X,A3,5X,A4,6X,A1,8X,A5,20X,A3,5X,A4,
*        6X,A1,12X,A4,4X,A5,7X,A6,2X,A7)
710 FORMAT (11X,A5,3X,A6,3X,A5,30X,A5,12X,A5,29X,A6,3X,A5)
715 FORMAT (1X, '(' ,A7,2X,A5,9X,A7,6X,A5,7X,A7,6X,A5,
*        10X,A7,10X,A11)
720 FORMAT (3X,A6, ')',3X,A4,10X,A4,9X,A4,8X,A4,9X,A4,
*        11X,A4,11X,A12)
725 FORMAT (3X,A5,5X,A4,10X,A4,9X,A4,8X,A4,9X,A4,11X,A4,9X,A14,
*        7X,A14)
730 FORMAT (' ',128('-'))
      LINES = 8
      END

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SUBROUTINE SETINI (TAPOG,TIME)
DOUBLE PRECISION TAPOG,TIME,ROUND,INTERV
ROUND = INT(.1*((TAPOG-TIME)/60.))
INTERV = TAPOG - TIME - 60.*(10.*ROUND)
TIME = TIME + INTERV
END

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SUBROUTINE INCRS (DIST,INIDIS,TIME,INCR)
DOUBLE PRECISION DIST,INIDIS,TIME,INCR
IF (DIST .EQ. INIDIS) THEN
  INCR = 0.
ELSE IF (DIST .LT. 50.) THEN
  INCR = .001
ELSE IF (DIST .LT. 600.) THEN
  INCR = .25
ELSE IF (DIST .LT. 1600.) THEN
  INCR = 60.
ELSE IF (DIST .LT. 3000.) THEN
  INCR = 600.
ELSE
  INCR = 1800.
END IF
TIME = TIME + INCR
END

```

```

SUBROUTINE TARORB (TAPOG, TIME, DDELTA, DELTA, VCIRX, VCIRY, RCIRX,
*          RCIRY, VSYNC, RSYNC)
DOUBLE PRECISION TAPOG, TIME, DDELTA, DELTA, VCIRX, VCIRY, RCIRX,
*          RCIRY, VSYNC, RSYNC
DELTA = (TAPOG - TIME)*DDELTA
VCIRX = -VSYNC*COS(DELTA)
VCIRY = VSYNC*SIN(DELTA)
RCIRX = RSYNC*SIN(DELTA)
RCIRY = RSYNC*COS(DELTA)
END
*****
*****
SUBROUTINE DISVEL (RCIRX, RELX, RCIRY, RELY, VCIRX, VELLX,
*          VCIRY, VELY, PI, DIST, VREL, LOS, DIRVEL)
DOUBLE PRECISION RCIRX, RELX, RCIRY, RELY, VCIRX, VELLX, VCIRY,
*          VELY, PI, DIST, VREL, LOS, DIRVEL
DIST = SQRT((RCIRX-REXX)**2 + (RCIRY-RELY)**2)
VREL = SQRT((VCIRX-VELLX)**2 + (VCIRY-VELY)**2)
LOS = ATAN((RCIRX-REXX)/(RCIRY-RELY))
IF (LOS .LT. 0.) THEN
    LOS = PI + LOS
END IF
DIRVEL = ATAN((VELLX-VCIRX)/(VELY-VCIRY))
IF (DIRVEL .LT. 0.) THEN
    DIRVEL = PI + DIRVEL
END IF
END
*****
*****
SUBROUTINE ASAFRE (N, TIME, PSI, E, A, MU, THETA, RELIP, BETA,
*          VELLIP, RELX, RELY, VELLX, VELY)
DOUBLE PRECISION N, TIME, PSI, E, A, MU, THETA, RELIP, BETA, VELLIP,
*          RELX, RELY, VELLX, VELY, M, PSI1
M = N*TIME
50 PSI1 = M + E*SIN(PSI)
IF ((ABS(PSI1-PSI)) .GT. (1E-11)) THEN
    PSI = PSI1
    GO TO 50
ELSE
    PSI = PSI1
END IF
THETA = ACOS((COS(PSI)-E)/(1.-E*COS(PSI)))
RELLIP = A*(1.-E*COS(PSI))
BETA = ACOS(SQRT(((A**2)*(1.-E**2))/(RELLIP*(2.*A-RELLIP))))
VELLIP = SQRT(MU*(2./RELLIP-1./A))
RELLX = RELIP*SIN(THETA)
RELY = -RELLIP*COS(THETA)
VELLX = VELLIP*COS(THETA-BETA)
VELLY = VELLIP*SIN(THETA-BETA)
END

```

```

SUBROUTINE DELTAV (ANGOFF,DISTAT,DELV,CYCLE)
DOUBLE PRECISION ANGOFF, DISTAT,DISOFF,DELV,CYC
INTEGER CYCLE
CYC = CYCLE
DISOFF = ANGOFF*DISTAT
DELV = DISOFF/CYC
END

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*****
*****
*****

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SUBROUTINE ASACHG (DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,ASAT,
*               TIMAST,THETAS,THETCR,BETAST,RELLX,RELY)
INTEGER ASAT
DOUBLE PRECISION DELV,THETA,PI,A,E,RELLIP,N,PSI,MU,TIMAST,
*               THETAS,THETCR,DELVS,DELVT,P,DELA,DELE,BETAST,
*               RELLX,RELY,DELAST,PSIANG,THTANG
DELAST = ATAN(RELLX/RELY)
DELVS = DELV * COS(DELAST)
DELVT = DELV * SIN(DELAST)
P = A*(1.-E**2)
DELA = 2*((DELVS*E*SIN(THETA)) + (P*DELVT/RELLIP))/(N*
*   Sqrt(1.-E**2))
DELE = (Sqrt(1.-E**2))*(DELVS*SIN(THETA) + DELVT*(COS(PSI)+
*   COS(THETA)))/(N*A)
A = A + DELA
E = E + DELE
N = Sqrt(MU/A**3)
PSIANG = (1.-RELLIP/A)/E
IF (PSIANG .LT. -1.) THEN
    PSI = PI
ELSE IF (PSIANG .GT. 1) THEN
    PSI = 0.
ELSE
    PSI = ACOS(PSIANG)
END IF
TIMAST = (PSI-E*SIN(PSI))/N
THTANG = (COS(PSI)-E)/(1.-E*COS(PSI))
IF (THTANG .LT. -1) THEN
    THETAS = PI
ELSE IF (THTANG .GT. 1) THEN
    THETAS = 0.
ELSE
    THETAS = ACOS(THTANG)
END IF
BETAST = ACOS(Sqrt(((A**2)*(1.-E**2))/(RELLIP*(2.*A-RELLIP))))
THETCR = THETCR + THETA - THETAS
IF (THETCR .GT. (2.*PI)) THEN
    THETCR = THETCR - 2.*PI
END IF
ASAT = 1
END

```

```

*****

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```

SUBROUTINE BALEJK (RSYNC, RCIRX, RCIRY, DELT, VELEJK, ANGEJK, VCIRX,
*
*          VCIRY, MU, RBALLN, RBALX, RBALY, VBALX, VBALY,
*          VBALLN, BALOON, TIBALN, BETBAL, ABALLN, EBALLN,
*          PSIBAL, THETEJ, NBALLN, DELTEJ)

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    INTEGER BALOON

```

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    DOUBLE PRECISION RSYNC, RCIRX, RCIRY, DELT, VELEJK, ANGEJK, VCIRX,
*
*          VCIRY, MU, RBALLN, RBALX, RBALY, VBALX, VBALY,
*          VBALLN, TIBALN, BETBAL, ABALLN, EBALLN, PSIBAL,
*          THETEJ, NBALLN, DELTEJ, VEJGX, VEJGY, ANGMOB

```

```

    RBALLN = RSYNC
    RBALX = RCIRX
    RBALY = RCIRY
    DELTEJ = DELT
    VEJGX = -VELEJK*COS(DELTEJ+ANGEJK)
    VEJGY = VELEJK*SIN(DELTEJ+ANGEJK)
    VBALX = VCIRX + VEJGX
    VBALY = VCIRY + VEJGY
    VBALLN = SQRT((VBALY)**2 + (VBALX)**2)
    BETBAL = ATAN(ABS(VBALY/VBALX))-DELTEJ
    ABALLN = RBALLN/(2.-(RBALLN)*(VBALLN**2)/MU))
    ANGMOB = RBALLN*VBALLN*COS(BETBAL)
    EBALLN = SQRT(1.-(ANGMOB**2)/(MU*ABALLN))
    PSIBAL = ACOS((ABALLN-RBALLN)/(ABALLN*EBALLN))
    THETEJ = 2*ATAN(SQRT((1.+EBALLN)/(1.-EBALLN))*TAN(PSIBAL/2.))
    NBALLN = SQRT(MU/ABALLN**3)
    TIBALN = (PSIBAL-EBALLN*SIN(PSIBAL))/NBALLN
    BALOON = 1
    END

```

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*****

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*****

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*****

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```

SUBROUTINE BALORB (TIBALN, INCR, NBALLN, PSIBAL, EBALLN, ABALLN, MU,
*
*          DELTEJ, THETEJ, PI, THETBA, RBALLN, BETBAL,
*          VBALLN, RBALX, RBALY, VBALX, VBALY)
    DOUBLE PRECISION TIBALN, INCR, NBALLN, PSIBAL, EBALLN, ABALLN, MU,
*
*          DELTEJ, THETEJ, PI, THETBA, RBALLN, BETBAL,
*          VBALLN, RBALX, RBALY, VBALX, VBALY, MBALLN, PSIBL1
    TIBALN = TIBALN + INCR
    MBALLN = NBALLN * TIBALN
90  PSIBL1 = MBALLN + EBALLN*SIN(PSIBAL)
    IF ((ABS(PSIBL1-PSIBAL)) .GT. (1E-9)) THEN
        PSIBAL = PSIBL1
        GO TO 90
    ELSE
        PSIBAL = PSIBL1
    END IF
    THETBA = ACOS((COS(PSIBAL)-EBALLN)/(1.-EBALLN*COS(PSIBAL)))
    RBALLN = ABALLN*(1.-EBALLN*COS(PSIBAL))
    BETBAL = ACOS(SQRT((ABALLN**2)*(1.-EBALLN**2)/(RBALLN*
*          (2.*ABALLN-RBALLN))))
    VBALLN = SQRT(MU*(2./RBALLN-1./ABALLN))
    RBALX = RBALLN*SIN(DELTEJ + THETEJ -THETBA)

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RBALY = RBALLN*COS(DELTEJ + THETEJ - THETBA)
VBALX = VBALLN*COS(PI-DELTEJ-THETEJ+THETBA-BETBAL)
VBALY = VBALLN*SIN(PI-DELTEJ-THETEJ+THETBA-BETBAL)
END
*****
*****
*****
      SUBROUTINE ASAORB (TIMAST,INCR,N,E,PSI,A,MU,THETCR,THETA,
*                      RELIP,BETA,VELLIP,RELLX,RELLY,VELLX,
*                      VELLY,PI)
      DOUBLE PRECISION TIMAST,INCR,N,E,PSI,A,MU,THETCR,THETA,RELIP,
*                      BETA,VELLIP,RELLX,RELLY,VELLX,VELLY,M,PSI1,
*                      PI
      TIMAST = TIMAST + INCR
      M = N*TIMAST
70  PSI1 = M + E*SIN(PSI)
      IF ((ABS(PSI1-PSI)) .GT. (1E-11)) THEN
        PSI = PSI1
        GO TO 70
      ELSE
        PSI = PSI1
      END IF
      THETA = ACOS((COS(PSI)-E)/(1.-E*COS(PSI)))
      RELIP = A*(1.-E*COS(PSI))
      BETA = ACOS(SQRT(((A**2)*(1.-E**2))/(RELIP*(2.*A-RELIP))))
      VELLIP = SQRT(MU*(2./RELIP-1./A))
      RELX = RELIP*SIN(PI-THETA-THETCR)
      RELY = RELIP*COS(PI-THETA-THETCR)
      VELLX = VELLIP*COS(THETA+THETCR-BETA)
      VELLY = VELLIP*SIN(THETA+THETCR-BETA)
      END
*****
*****
*****
      SUBROUTINE RSPONS (ANGLE,RESP,CONS)
      DOUBLE PRECISION ANGLE,RESP,CONS,X
      X = ANGLE * 1000.
      IF (X .LE. 20) THEN
        RESP = EXP(-X/CONS)
      ELSE IF (X .LE. 40) THEN
        RESP = .15
      ELSE IF (X .LE. 50) THEN
        RESP = .15 - .015*(X-40.)
      ELSE
        RESP = 0.
      END IF
      END
*****

```



```

SUBROUTINE SNSOUT (OFAXRE,INTENS,SEPAR,SIGNAL)
DOUBLE PRECISION OFAXRE,INTENS,SEPAR,SIGNAL
SIGNAL = (OFAXRE*INTENS)/(SEPAR**2)
END

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SUBROUTINE DISLOS (DIST,RBALX,RELLX,RBALY,RELLY,PI,RCIRX,
*          RCIRY,LOSAB,LOSAT,LOSBT,DISTAB,DISTAT,DISTBT,LOS)
DOUBLE PRECISION DIST,RBALX,RELLX,RBALY,RELLY,PI,RCIRX,
*          RCIRY,LOSAB,LOSAT,LOSBT,DISTAB,DISTAT,DISTBT,LOS
DISTAT = DIST
DISTAB = SQRT((RBALX-RELLX)**2 + (RBALY-RELLY)**2)
DISTBT = SQRT((RBALX-RCIRX)**2 + (RBALY-RCIRY)**2)
LOSAB = ATAN((RBALX-RELLX)/(RBALY-RELLY))
IF (LOSAB .LT. 0.) THEN
    LOSAB = PI + LOSAB
END IF
LOSAT = LOS
LOSBT = ATAN((RBALX-RCIRX)/(RBALY-RCIRY))
IF (LOSBT .LT. 0.) THEN
    LOSBT = PI + LOSBT
END IF
END

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SUBROUTINE ANGLE (DISTAT,DISTAB,DISTBT,LOSAT,LOSAB,LOSBT,
*          LOSLST,ALPHA,B,T)
DOUBLE PRECISION DISTAT,DISTAB,DISTBT,LOSAT,LOSAB,LOSBT,
*          LOSLST,ALPHA,B,T,S,R
S = (DISTAT + DISTAB + DISTBT)/2.
R = SQRT((S-DISTAT)*(S-DISTAB)*(S-DISTBT)/S)
ALPHA = 2*ATAN(R/(S-DISTBT))
B = ABS(LOSLST - LOSAB)
T = ABS(LOSLST - LOSAT)
END

```

\*\*\*\*\*

```

SUBROUTINE CENTRD (B,FOV,T,LOSLST,LOSAT,LOSAB,ALPHA,BALCUR,
*          TARCUR,DISTAT,VREL,PI,DIRVEL,STATUS,LOSCEN,
*          ANGOFF,DISTAB,CYCLE)
CHARACTER STATUS*16
INTEGER CYCLE
DOUBLE PRECISION B,FOV,T,LOSLST,LOSAT,LOSAB,ALPHA,BALCUR,
*          TARCUR,DISTAT,VREL,PI,DIRVEL,LOSCEN,ANGOFF,
*          OMEGA,CYC,DISTAB
CYC = CYCLE
IF ((B .GT. FOV) .AND. (T .GT. FOV)) THEN
    LOSCEN = LOSLST
    IF (DISTAT .GT. (VREL*CYC)) THEN
        STATUS = 'NEITHER IN FOV'
    END IF
END IF

```

```

ELSE IF (B .GT. FOV) THEN
  LOSCEN = LOSAT
  IF (DISTAT .GT. (VREL*CYC)) THEN
    STATUS = 'DECOY OUT OF FOV'
  END IF
ELSE IF (T .GT. FOV) THEN
  LOSCEN = LOSAB
  IF (DISTAT .GT. (VREL*CYC)) THEN
    STATUS = 'TARGT OUT OF FOV'
  END IF
ELSE
  OMEGA = ALPHA*(BALCUR/(BALCUR + TARCUR))
  IF (LOSAT .GT. LOSAB) THEN
    LOSCEN = LOSAT - OMEGA
  ELSE IF (LOSAT .LT. LOSAB) THEN
    LOSCEN = LOSAT + OMEGA
  ELSE
    LOSCEN = LOSAT
  END IF
END IF
ANGOFF = LOSLST - LOSCEN
END
*****
*****
*****
SUBROUTINE CHKHIT (DISTAT,DIAM,RCIRX,RELLX,STATUS)
CHARACTER STATUS*16
DOUBLE PRECISION DISTAT,DIAM,RCIRX,RELLX,HITDIS
HITDIS = SQRT((DIAM**2) + ((RCIRX-RELLX)**2))
IF (DISTAT .LE. HITDIS) THEN
  STATUS = 'TARGET HIT'
ELSE
  STATUS = 'ASAT DECOYED'
END IF
END
*****
*****
*****
SUBROUTINE PGRAF (IBAL,ITARG,AEJ)
DOUBLE PRECISION IBAL,ITARG,AEJ
REAL XTERM,YTERM
XTERM = AEJ
YTERM = IBAL/ITARG
WRITE (3,300) XTERM,YTERM
300 FORMAT (1X,F11.4,' '.F11.4)
END
*****

```

```

SUBROUTINE PDATA1 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSYN,
*      VCIRX,VCIRY,THETA,BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,
*      VELLX,VELLY,DIST,VREL,DIRVEL,LOS,TIME,TAPOG,BTITS)
  INTEGER LINES
  REAL TIMEP,ASTHET,ASBETA,ASATE,ASTPSI,ASATA,ASATR,ASATRX,ASATRY,
*      ASATV,ASATVX,ASATVY,TRGDLT,TARGR,TARGRX,TARGRY,TARGV,
*      TARGVX,TARGVY,ATDIS,ATRELV,ATDRRV,ATLOS,TIMETO
  DOUBLE PRECISION DELT,RSYNC,RCIRX,RCIRY,VSYN,VCIRX,VCIRY,THETA,
*      BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,VELLX,VELLY,DIST,
*      VREL,DIRVEL,LOS,TIME,TAPOG,BTITS
  CHARACTER STATUS*16
  TIMEP = (BTITS+TIME-TAPOG)/60.
  TIMETO = (TAPOG-TIME)/60.
  TRGDLT = DELT
  TARGR = RSYNC
  TARGRX = RCIRX
  TARGRY = RCIRY
  TARGV = VSYN
  TARGVX = VCIRX
  TARGVY = VCIRY
  ASTHET = THETA
  ASBETA = BETA
  ASATE = E
  ASTPSI = PSI
  ASATA = A
  ASATR = RELLIP
  ASATRX = RELLX
  ASATRY = RELLY
  ASATV = VELLIP
  ASATVX = VELLX
  ASATVY = VELLY
  ATDIS = DIST
  ATRELV = VREL
  ATDRRV = DIRVEL
  ATLOS = LOS
  WRITE (4,800) TIMEP,ASTPSI,ASBETA,ASATE,TRGDLT,ATDIS,ATLOS,
*      ATRELV,ATDRRV
  WRITE (4,801) ASTHET,ASATA
  WRITE (4,802) TIMETO,ASATR,ASATV,TARGR,TARGV,STATUS
  WRITE (4,803) ASATRX,ASATVX,TARGRX,TARGVX
  WRITE (4,804)
800  FORMAT (' ',F8.3,1X,F7.4,1X,F7.4,1X,F9.6,2X,F7.4,45X,F11.4,
*      ' / ',F8.5,2X,F8.5,1X,F7.4)
801  FORMAT (10X,F5.2,5X,'---',3X,F9.2)
802  FORMAT (1X,F8.3,1X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,54X,A16)
803  FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7)
804  FORMAT (' ',128('-'))
  LINES = LINES + 6
  END
*****

```

```

SUBROUTINE PDATA2 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSYNC,
*      VCIRX,VCIRY,THETA,BETA,E,PSI,A,RELLIP,RELLX,RELLY,
*      VELLIP,VELLX,VELLY,DIST,VREL,DIRVEL,LOS,TIME,TAPOG,
*      BTITS, DELV)
INTEGER LINES
REAL TIMEP,ASTHET,ASBETA,ASATE,ASTPSI,ASATA,ASATR,ASATRX,ASATRY,
*      ASATV,ASATVX,ASATVY,TRGDLT,TARGR,TARGRX,TARGRY,TARGV,
*      TARGVX,TARGVY,ATDIS,ATRELV,ATDRRV,ATLOS,TIMETO
DOUBLE PRECISION DELT,RSYNC,RCIRX,RCIRY,VSYNC,VCIRX,VCIRY,
*      THETA,BETA,E,PSI,DELV,A,RELLIP,RELLX,RELLY,DIST,
*      LOS,TIME,TAPOG,BTITS,VELLIP,VELLX,VELLY,VREL,DIRVEL
CHARACTER STATUS*16
TIMEP = (BTITS+TIME-TAPOG)/60.
TIMETO = (TAPOG-TIME)/60.
TRGDLT = DELT
TARGR = RSYNC
TARGRX = RCIRX
TARGRY = RCIRY
TARGV = VSYNC
TARGVX = VCIRX
TARGVY = VCIRY
ASTHET = THETA
ASBETA = BETA
ASATE = E
ASTPSI = PSI
ASATA = A
ASATR = RELLIP
ASATRX = RELLX
ASATRY = RELLY
ATDIS = DIST
ATLOS = LOS
ASATV = VELLIP
ASATVX = VELLX
ASATVY = VELLY
ATRELV = VREL
ATDRRV = DIRVEL
WRITE (4,810) TIMEP,ASTPSI,ASBETA,ASATE,TRGDLT,ATDIS,ATLOS,
*      ATRELV,ATDRRV
WRITE (4,811) ASTHET,DELV,ASATA
WRITE (4,812) TIMETO,ASATR,ASATV,TARGR,TARGV,STATUS
WRITE (4,813) ASATRX,ASATVX,TARGRX,TARGVX
WRITE (4,813) ASATRY,ASATVY,TARGRY,TARGVY
WRITE (4,814)
810 FORMAT (' ',F8.3,1X,F7.4,1X,F7.4,1X,F9.6,2X,F7.4,45X,F11.4,
*      ' / ',F8.5,2X,F8.5,1X,F7.4)
811 FORMAT (10X,F5.2,1X,D9.3,1X,F9.2)
812 FORMAT (1X,F8.3,1X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,54X,A16)
813 FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7)
814 FORMAT (' ',128('-'))
LINES = LINES + 6
END

```

```

SUBROUTINE PDATA3 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSYNC,
*      VCIRX,VCIRY,THETA,BETA,E,PSI,A,RELLIP,RELLX,RELLY,
*      VELLIP,VELLX,VELLY,DIST,VREL,DIRVEL,LOS,TIME,TAPOG,
*      BTITS,THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,RBALLN,
*      RBALX,RBALY,VBALLN,VBALX,VBALY)
INTEGER LINES
REAL TIMEP,ASTHET,ASBETA,ASATE,ASTPSI,ASATA,ASATR,ASATRX,ASATRY,
*      ASATV,ASATVX,ASATVY,TRGDLT,TARGR,TARGRX,TARGRY,TARGV,
*      TARGVX,TARGVY,BLTHET,BLBETA,BALLNE,BALPSI,BALLNA,BALLNR,
*      BALNRX,BALNRY,BALLNV,BALNVX,BALNVY,ATDIS,ABDIS,ATRELV,
*      ATDRRV,ATLOS,ABLOS,BTDIS,TIMETO
DOUBLE PRECISION DELT,RSYNC,RCIRX,RCIRY,VSYNC,VCIRX,VCIRY,THETA,
*      BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,VELLX,VELLY,DIST,
*      VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,THETEJ,BETBAL,EBALLN,
*      PSIBAL,ABALLN,RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY
CHARACTER STATUS*16
TIMEP  = (BTITS+TIME-TAPOG)/60.
TIMETO = (TAPOG-TIME)/60.
TRGDLT = DELT
TARGR  = RSYNC
TARGRX = RCIRX
TARGRY = RCIRY
TARGV  = VSYNC
TARGVX = VCIRX
TARGVY = VCIRY
ASTHET = THETA
ASBETA = BETA
ASATE  = E
ASTPSI = PSI
ASATA  = A
ASATR  = RELLIP
ASATRX = RELLX
ASATRY = RELLY
ASATV  = VELLIP
ASATVX = VELLX
ASATVY = VELLY
ATDIS  = DIST
ATRELV = VREL
ATDRRV = DIRVEL
ATLOS  = LOS
BLTHET = THETEJ
BLBETA = BETBAL
BALLNE = EBALLN
BALPSI = PSIBAL
BALLNA = ABALLN
BALLNR = RBALLN
BALNRX = RBALX
BALNRY = RBALY
BALLNV = VBALLN
BALNVX = VBALX
BALNVY = VBALY
ABDIS  = DIST

```

```

ABLOS = LOS
BTDIS = 0.
WRITE (4,820) TIMEP,ASTPSI,ASBETA,ASATE,TRGDLT,BALPSI,BLBETA,
*      BALLNE,ATDIS,ATLOS,ATRELV,ATDRRV
WRITE (4,821) ASTHET,ASATA,BLTHET,BALLNA,ABDIS,ABLOS
WRITE (4,822) TIMETO,ASATR,ASATV,TARGR,TARGV,BALLNR,
*      BALLNV,BTDIS,STATUS
WRITE (4,823) ASATRX,ASATVX,TARGRX,TARGVX,BALNRX,BALNVX
WRITE (4,823) ASATRY,ASATVY,TARGRY,TARGVY,BALNRY,BALNVY
WRITE (4,824)
820  FORMAT (' ',F8.3,1X,F7.4,1X,F7.4,1X,F9.6,2X,F7.4,18X,F7.4,1X,
*          F7.4,1X,F9.6,2X,F11.4,' / ',F8.5,2X,F8.5,1X,F7.4)
821  FORMAT (10X,F5.2,5X,'---',3X,F9.2,27X,F5.2,11X,F9.2,2X,
*          F11.4,' / ',F8.5)
822  FORMAT (1X,F8.3,1X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,
*          F10.3,4X,F10.7,3X,F11.4,' / ',2X,'---',5X,A16)
823  FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,F10.3,4X,F10.7)
824  FORMAT (' ',128('-'))
      LINES = LINES + 6
      END
*****
*****
*****
      SUBROUTINE PDATA4 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSYN,
*          VCIRX,VCIRY,THETA,BETA,E,PSI,A,RELLIP,RELLX,RELLY,
*          VELLIP,VELLX,VELLY,DIST,VREL,DIRVEL,LOS,TIME,TAPOG,
*          BTITS,THETEJ,BETBAL,EBALLN,PSIBAL,ABALLN,RBALLN,
*          RBALX,RBALY,VBALLN,VBALX,VBALY,DELV)
      INTEGER LINES
      REAL TIMEP,ASTHET,ASBETA,ASATE,ASTPSI,ASATA,ASATR,ASATRX,ASATRY,
*          ASATV,ASATVX,ASATVY,TRGDLT,TARGR,TARGRX,TARGRY,TARGV,
*          TARGVX,TARGVY,BLTHET,BLBETA,BALLNE,BALPSI,BALLNA,BALLNR,
*          BALNRX,BALNRY,BALLNV,BALNVX,BALNVY,ATDIS,ABDIS,ATRELV,
*          ATDRRV,ATLOS,ABLOS,BTDIS,TIMETO
      DOUBLE PRECISION DELT,RSYNC,RCIRX,RCIRY,VSYN,VCIRX,VCIRY,THETA,
*          BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,VELLX,VELLY,DIST,
*          VREL,DIRVEL,LOS,TIME,TAPOG,BTITS,THETEJ,BETBAL,EBALLN,
*          PSIBAL,ABALLN,RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY,DELV
      CHARACTER STATUS*16
      TIMEP = (BTITS+TIME-TAPOG)/60.
      TIMETO = (TAPOG-TIME)/60.
      TRGDLT = DELT
      TARGR = RSYNC
      TARGRX = RCIRX
      TARGRY = RCIRY
      TARGV = VSYN
      TARGVX = VCIRX
      TARGVY = VCIRY
      ASTHET = THETA
      ASBETA = BETA

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```

ASATE = E
ASTPSI = PSI
ASATA = A
ASATR = RELIP
ASATRX = RELX
ASATRY = RELY
ASATV = VELLIP
ASATVX = VELLX
ASATVY = VELLY
ATDIS = DIST
ATRELV = VREL
ATDRRV = DIRVEL
ATLOS = LOS
BLTHET = THETEJ
BLBETA = BETBAL
BALLNE = EBALLN
BALPSI = PSIBAL
BALLNA = ABALLN
BALLNR = RBALLN
BALNRX = RBALX
BALNRY = RBALY
BALLNV = VBALLN
BALNVX = VBALX
BALNVY = VBALY
ABDIS = DIST
ABLOS = LOS
BTDIS = 0.
WRITE (4,820) TIMEP,ASTPSI,ASBETA,ASATE,TRGDLT,BALPSI,BLBETA,
*          BALLNE,ATDIS,ATLOS,ATRELV,ATDRRV
WRITE (4,821) ASTHET,DELV,ASATA,BLTHET,BALLNA,ABDIS,ABLOS
WRITE (4,822) TIMETO,ASATR,ASATV,TARGR,TARGV,BALLNR,BALLNV,
*          BTDIS,STATUS
WRITE (4,823) ASATRX,ASATVX,TARGRX,TARGVX,BALNRX,BALNVX
WRITE (4,823) ASATRY,ASATVY,TARGRY,TARGVY,BALNRY,BALNVY
WRITE (4,824)
820  FORMAT (1X,F8.3,1X,F7.4,1X,F7.4,1X,F9.6,2X,F7.4,18X,F7.4,1X,
*          F7.4,1X,F9.6,2X,F11.4,' / ',F8.5,2X,F8.5,1X,F7.4)
821  FORMAT (10X,F5.2,1X,D9.3,1X,F9.2,27X,F5.2,11X,F9.2,2X,
*          F11.4,' / ',F8.5)
822  FORMAT (1X,F8.3,1X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,
*          F10.3,4X,F10.7,3X,F11.4,' / ',2X,'---',5X,A16)
823  FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,F10.3,4X,F10.7)
824  FORMAT (' ',128('-'))
      LINES = LINES + 6
      END
*****
*****

```

```

SUBROUTINE PDATA5 (LINES,STATUS,DELT,RSYNC,RCIRX,RCIRY,VSINC,
*   VCIRX,VCIRY,THETA,BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,
*   VELLX,VELLY,DISTAT,VREL,DIRVEL,LOSAT,TIME,TAPOG,BTITS,
*   THETBA,BETBAL,EBALLN,PSIBAL,ABALLN,RBALLN,RBALX,RBALY,
*   VBALLN,VBALX,VBALY,DISTAB,DISTBT,LOSAB,LOSBT)
INTEGER LINES
REAL TIMEP,ASTHET,ASBETA,ASATE,ASTPSI,ASATA,ASATR,ASATRX,
*   ASATRY,ASATV,ASATVX,ASATVY,TRGDLT,TARGR,TARGRX,TARGRY,
*   TARGV,TARGVX,TARGVY,BLTHET,BLBETA,BALLNE,BALPSI,BALLNA,
*   BALLNR,BALNRX,BALNRY,BALLNV,BALNVX,BALNVY,ATDIS,ABDIS,
*   BTDIS,ATRELV,ATDRRV,ATLOS,ABLOS,BTLOS,TIMETO
DOUBLE PRECISION DELT,RSYNC,RCIRX,RCIRY,VSINC,VCIRX,VCIRY,THETA,
*   BETA,E,PSI,A,RELLIP,RELLX,RELLY,VELLIP,VELLX,VELLY,VREL,
*   DIRVEL,TIME,TAPOG,BTITS,THETBA,BETBAL,EBALLN,PSIBAL,
*   ABALLN,RBALLN,RBALX,RBALY,VBALLN,VBALX,VBALY,DISTAB,
*   DISTBT,LOSAB,LOSBT,LOSAT,DISTAT
CHARACTER STATUS*16
TIMEP  = (BTITS+TIME-TAPOG)/60.
TIMETO = (TAPOG-TIME)/60.
TRGDLT = DELT
TARGR  = RSYNC
TARGRX = RCIRX
TARGRY = RCIRY
TARGV  = VSINC
TARGVX = VCIRX
TARGVY = VCIRY
ASTHET = THETA
ASBETA = BETA
ASATE  = E
ASTPSI = PSI
ASATA  = A
ASATR  = RELIP
ASATRX = RELX
ASATRY = RELY
ASATV  = VELLIP
ASATVX = VELLX
ASATVY = VELLY
BLTHET = THETBA
BLBETA = BETBAL
BALLNE = EBALLN
BALPSI = PSIBAL
BALLNA = ABALLN
BALLNR = RBALLN
BALNRX = RBALX
BALNRY = RBALY
BALLNV = VBALLN
BALNVX = VBALX
BALNVY = VBALY
ABDIS  = DISTAB
ATDIS  = DISTAT

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ATRELV = VREL
ATDRRV = DIRVEL
ATLOS = LOSAT
BTDIS = DISTBT
ABLOS = LOSAB
BTLOS = LOSBT
WRITE (4,830) TIMEP,ASTPSI,ASBETA,ASATE,TRGDLT,BALPSI,BLBETA,
*          BALLNE,ATDIS,ATLOS,ATRELV,ATDRRV
WRITE (4,831) ASTHET,ASATA,BLTHET,BALLNA,ABDIS,ABLOS,STATUS
WRITE (4,832) TIMETO,ASATR,ASATV,TARGR,TARGV,BALLNR,BALLNV,
*          BTDIS,BTLOS
WRITE (4,833) ASATRX,ASATVX,TARGRX,TARGVX,BALNRX,BALNVX
WRITE (4,834) ASATRY,ASATVY,TARGRY,TARGVY,BALNRY,BALNVY
WRITE (4,835)
830  FORMAT (1X,F8.3,1X,F7.4,1X,F7.4,1X,F9.6,2X,F7.4,18X,F7.4,1X,
*          F7.4,1X,F9.6,2X,F11.4,' / ',F8.5,2X,F8.5,1X,F7.4)
831  FORMAT (10X,F5.2,5X,'---',3X,F9.2,27X,F5.2,11X,F9.2,2X,F11.4,
*          ' / ',F8.5,2X,A16)
832  FORMAT (1X,F8.3,1X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,F10.3,
*          4X,F10.7,3X,F11.4,' / ',F8.5,' B/T RATIO: ')
833  FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,F10.3,4X,F10.7,
*          26X,' NOT DETERMINED ')
834  FORMAT (11X,F10.3,4X,F10.7,3X,F10.3,2X,F10.7,3X,F10.3,4X,F10.7)
835  FORMAT (' ',128('-'))
      LINES = LINES + 6
      END

```

### Appendix C

A sample of the abbreviated tabular output from the program is given.



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→ This thesis examined the correlation between selected parameters characteristic of an infrared-guided anti-satellite attack against a geosynchronous target. The countermeasure employed was a balloon decoy. The criteria used to evaluate the parameters was the balloon-to-target ratio, measured at the output of a seeker detector. Specific design of the seeker detector, ASAT weapon and the balloon decoy were not addressed in this study. Coplanar orbits were assumed for all vehicles, with the target intercept point coincidental with the ASAT orbit's apogee. The ASAT endgame was modeled and implemented on a digital computer. Decoy parameters investigated were the weapon-target range at time of decoy ejection, the magnitude and direction of the balloon velocity at ejection. The field of view of the seeker was also considered. Results indicated a minimum balloon-to-target ratio needed, corresponding to selected nominal values of remaining parameters, to decoy the ASAT weapon. *Key words: Infrared decoy, ASAT, geosynchronous target, balloon decoy, seeker detector, weapon-target range, balloon velocity, field of view, minimum balloon-to-target ratio.*